ADDING VALUE USING EM SENSOR ARRAY DESIGNED FOR A RUN OUT TABLE*

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Abstract

Electromagnetic based (EM) sensor technology has been shown to detect changes in the magnetic permeability of steel strip travelling down the run out table after rolling. Measuring below the Curie temperature, these changes can be interpreted in terms of the phase transformation from austenite (paramagnetic) to ferrite (ferromagnetic). These real time measurements provide a detailed insight into the changes in the structure at high temperature providing the steel producer with feedback on quality control, product consistency and product development. However unlike mill microstructure models, the sensor measurement provides a point reading at a distance through the cooling course. To map the transformation in more detail, a sensor array is required along the length of the Run Out Table i.e. to measure points on the austenite to ferrite transformation curve. This paper describes the process and metallurgical factors that should be considered in the optimum design of a sensor array, i.e. the number and location of the sensor heads. Examples of cooling strategies for different steel grades e.g. low carbon, structural and dual phase steels are used to demonstrate the importance of sensor location. In addition, the effect of variability within typical industrial parameters e.g. cooling speed, on the sensitivity of sensor output and location will be considered.

Keywords: Electromagnetic sensor; Phase Transformation; Microstructure.

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1 INTRODUCTION

Steels offer a refined, sophisticated and low cost option for a vast range of engineering applications. This diversity is intrinsically linked to the many phase transformations and processing variables during their production. These can be exploited and developed to achieve a large range of desirable properties from a large range of final structures [1].

The Level 2 process and simulation models that control the rolling process in steel mills require calibration and validation to achieve stable consistent production in the industrial environment. Inputs for this have two main sources; results from offline Quality Assurance (QA) activities (e.g. characterization of the structure and mechanical property relationships) and measurements from different in-line sensor technologies.

With respect to the direct measurement of the passing steel structure, established sensor technologies are generally limited to the cold state. These non-destructive testing (NDT) techniques include ultrasonic (US) and electromagnetic (EM) based sensors. For example, US acoustic resonance techniques can assess defects structures in pipeline welds. In comparison EM sensors are a well-established technology to provide a range of measurements for cold rolled and surface-coated strip steels. This application requires a correlation between the sensor output and the mechanical properties. Potential benefits include the in-line assessment of product quality and the optimization of upstream parameters for subsequent production runs.

For a steel mill operator to achieve excellent process consistency over a wide product mix, integrated in-line sensor technologies that monitor through process structure property relationships at key stages are desired. One integral aspect of this engineering challenge is to develop and apply sensor technologies upstream; into the hot rolling stage of the process route, where in-situ feedback control can have a first positive effect.

This paper introduces an emerging application of EM sensor technology. These sensors are an integral part of the Transformation Monitor system which can be installed on the Run Out Table (ROT) in steel strip production. The Transformation Monitor is an array of EM sensors that are used to measure the austenite to ferrite phase transformation. The underlying physical metallurgical principles are reviewed along with a brief description and background to the sensor technology. The key process and metallurgical factors for the design of the sensor array are discussed. Examples based on typical cooling strategies for different steel grades are provided and with a number of practical aspects that also should be considered.

2 THE APPLICATION OF EM SENSORS IN A TRANSFORMATION MONITOR SYSTEM

Hot rolling is one of the most important stages in the production of steel strip. It typically ends with the hot strip undergoing a cooling process on the ROT prior to being coiled. It is common practice for a steel producer to target a finish rolling temperature and a coiling temperature. The desired cooling course (temperature loss and cooling rate) is determined by these temperatures and the target microstructure in the coil. In practice this is determined by the strip speed, the applied volume and distribution of cooling water and the decomposition of austenite (phase transformation) on the ROT.

In Level 2 control systems, temperature measurements from in-line pyrometers are used in combination with thermodynamic and kinetic phase transformation models to control to cooling process. It is not uncommon that the phase transformation is not well predicted by the models. Potential reasons for this include incomplete knowledge or model parameters (particularly with respect to the start of transformation or more complex phases) and inaccurate or inadequate modelling of the upstream processing and microstructure evolution (i.e. condition of the untransformed austenite). The likelihood increases when more complex and sophisticated steel grades are rolled.

2.1 Opportunities for EM Sensors

During the continuous cooling of steel, the austenite to ferrite transformation may start above or below the Curie temperature depending on the composition and cooling rate. The application of typical industrial controlled cooling strategies forces many steel grades to transform below the Curie temperature. Therefore real time in-line measurement of phase transformation (i.e. the transformation from paramagnetic austenite to ferromagnetic ferrite) on the ROT represents a clear opportunity for non-contact EM sensor technology.

The sensors are integral to the 1st generation Transformation Monitor system. The key features and benefits of this system can be summarized as follows:

1) Real time in-line measurements of the austenite to ferrite transformation for a wide range of grades and cooling strategies.

2) Validation of offline / in-line thermodynamic and kinetic phase transformation models.

3) A series of 'fingerprint' signals during cooling. These can be used to assess the influence and consistency of processing parameters and product uniformity; improve optimization of process routes for new grades.

2.2 The Underlying Physical Properties

The magnetic and electric properties of steel grades vary depending on alloy content, microstructure, temperature and high temperature processing parameters [2, 3]. These properties are intrinsically interdependent. For example, alloy content and processing parameters may combine to achieve a finer microstructure which in turn reduces magnetic permeability whilst increasing electrical resistivity.

Electrical resistivity is known to increase with alloy content and has a strong dependency with temperature [4]. Similarly thermomagnetic curves for ferromagnetic materials also show a clear dependency on temperature. Typically there is a peak in the curve as the temperature approaches the Curie point. This is known as the Hopkinson effect, first observed in studies on iron. Figure 1 illustrates the effect of temperature on the relative initial permeability (μ_0) for iron.

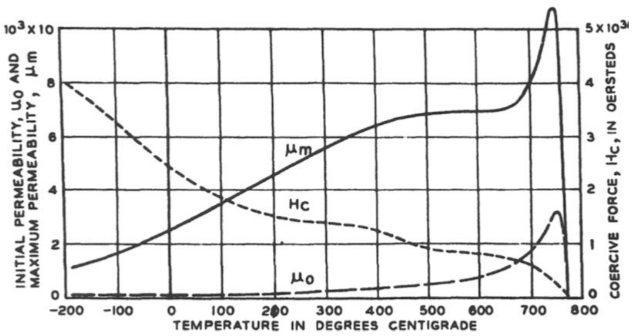

Figure 1. Temperature dependency of initial magnetic permeability μ_0 for iron [2].

3 EM SENSOR CHALLENGES

The sensor technology described in this paper uses the electromagnetic principles outlined in Section 2.2. The sensors have been developed through research at institutions in the UK, most recently the University of Manchester and the University of Warwick. The sensor in the Transformation Monitor array uses EMspec™ technology from the University of Manchester. These devices are low field

EM sensors which are sensitive to the relative initial permeability (μ_0); the shape of a typical thermomagnetic curve is shown in Figure 1. Although this sensing principle has been understood for some time [5, 6, 7], an in-line high temperature quantitative measurement of the austenite to ferrite phase transformation has only recently become available. Two major challenges that have been addressed to realize this potential are discussed in this section. They are:

1. Robust industrialization of sensors; protection in a harsh environment.
2. How to interpret the sensor measurements with respect to the evolving microstructure.

3.1 Industrialization of the EM Sensor

To ensure that the sensor provides reliable, consistent measurements in the harsh ROT environment it is essential that it is robust and well-engineered. Prototypes built by the University of Manchester proved the sensing principle [8]. For long term service, Primetals Technologies Ltd. have engineered and manufactured the current sensor head design and housing The EMspec^{TM} sensor consists of an H shaped non-conducting ferrite core with 1 exciting coil and 2 sensing coils (1 active, 1 dummy) which is shown in Figure 2 [9].

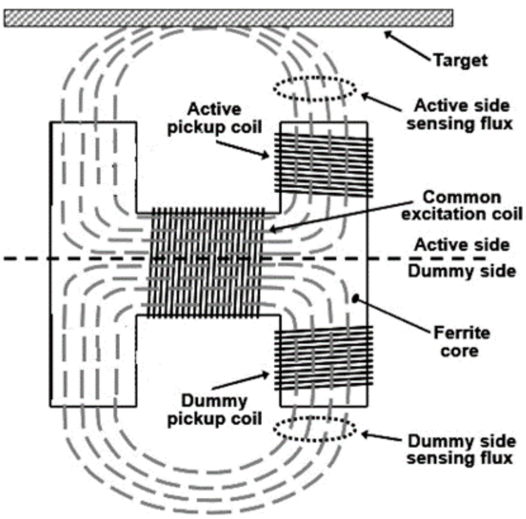

Figure 2. A schematic diagram of an H shaped sensor such as the type used in the EMspec^{TM}. [8]

As an overview, the active sensing coil detects voltage induced in the steel by the exciting coil while the dummy coil combined with the sensing coil zeros the signal when no steel is present. The EMspec^{TM} exciting coil runs simultaneously at 8 frequencies up to 48 kHz with a low magnetic field experienced by the target steel. Further details are provided by Hunt et al. [10]. The sensor head is relatively small and is enclosed within a ferritic stainless steel canister. This is a standard module which in turn is mounted into an environmental housing (Figure 3).

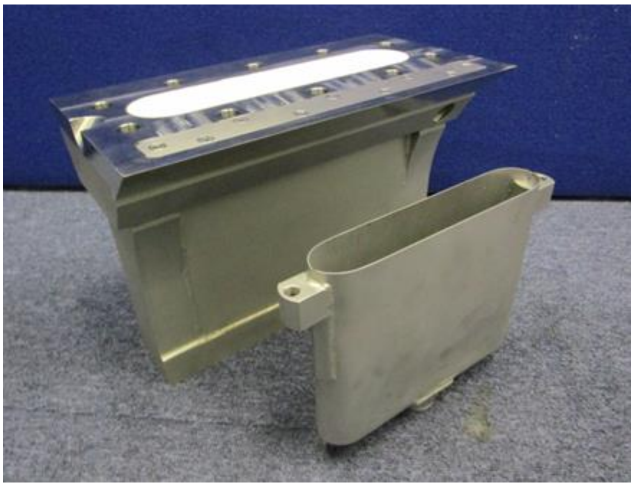

Figure 3. The sensor module and housing [10].

The housing protects the EMspec^{TM} sensor from heat and potential impact from the passing steel. Features of the housing include a cooling water jacket and exchangeable ceramic cover. The cover not only provides damage protection but also provides a necessary aperture for the electromagnetic field to pass through.

A pilot Transformation Monitor system was installed in the ROT at TATA Steel Europe IJmuiden Hot Strip Mill #2 in the Netherlands. The system, which has 3 EMspec^{TM} sensors, has been running successfully in the production environment for over 2 years. Yang et al. [11] initially described in detail the steps taken to ensure that the quantitative measurements of phase transformation were considered reliable and repeatable. Key variables included the alloy content, temperature and calibration of the sensors within their local environment (position in the ROT). The performance of the pilot Transformation Monitor was evaluated by comparing the interpretation of the sensor results with predictions from offline and in-line physically-based thermodynamic and metallurgical phase transformation mill models. More recent developments by Yang et al. [12] have demonstrated the importance of calibration between multiple sensors to ensure that the progressing transformation along the ROT is measured with confidence. For strips up to a thickness of ≈ 6mm, the measured and predicted results showed good agreement. It was also reported that for more complex steel grades, the Transformation Monitor system becomes more valuable for real time monitoring of the evolution of the microstructure on the ROT; i.e. quantitatively measuring the amount of transformation. The measurements may be used to improve the offline and inline physical thermodynamic and kinetic phase transformation models [12].

This initial work successfully demonstrated that the pilot Transformation Monitor system is able to quantitatively measure transformation in an accurately and reliably.

3.2 Interpretation of the Sensor Signal

A key aspect to the industrialization of the EMspec™ sensors is the correct interpretation of the output signals with respect to the passing steel microstructure. This is a fundamental step in creating accuracy and confidence in the Transformation Monitor system and requires knowledge of the underlying high temperature physical properties briefly introduced in section 2.2.

For each EMspec™ sensor, the inductance versus frequency spectrum is calculated. The zero-crossing frequency (ZCF) is the output signal from the 1st generation system. This is defined as the frequency at which the real inductance equals zero; or when the phase angle of the inductance spectra equals -90°. It is deduced from the calculated inductance phase spectra. The phase angle of the inductance spectra response to different targets is described in [13]. The ZCF is a function of the steel microstructure (phase fraction) through relationships between permeability and resistivity with microstructure and temperature. At high temperatures, ZCF values increase rapidly because low field relative permeability and resistivity values also increase with temperature.

Combining the 3D FE models described by Shen et al. [9], Figure 3 shows the % changes in the modelled ZCF output from the FE sensor model for mixed ferrite-austenite microstructures over the range of 0 to 100% ferrite fraction.

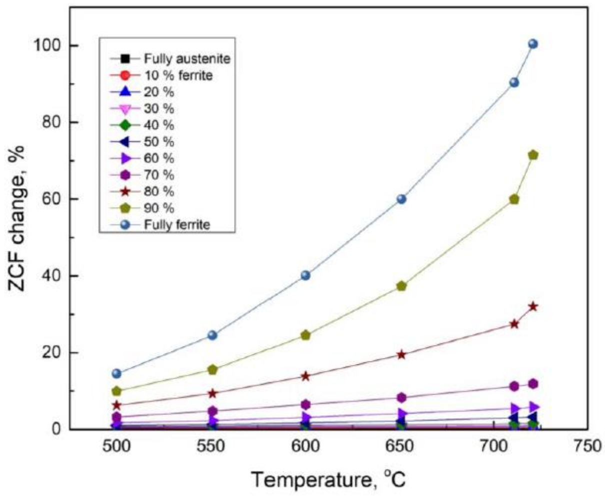

Figure 3. Predicted ZCF values for ferrite-austenite microstructures (0-100% ferrite) against temperature [8].

The results are plotted with respect to the value of maximum difference, i.e. as in Equation (1) where Max_{ZCF} is for ferrite at 721°C and Min_{ZCF} is for austenite at room temperature.

$$ZCF\ \%\ change = \frac{X_{ZCF} - Min_{ZCF}}{Max_{ZCF} - Min_{ZCF}} \quad (1)$$

The model has been verified by room temperature and high temperature experiments on various steel grades with a range of microstructure and thicknesses [9]. The results from this model are used to measure the austenite to ferrite phase transformation on the ROT from the array of EMspec™ signals from the Transformation Monitor.

4 THE TRANSFORMATION MONITOR – AN EM SENSOR ARRAY

It is typical that a microstructure model for a cooling section would predict the phase transformation along the entire length of the ROT i.e. transformation with respect to temperature and distance from the last mill stand. The use of a single EM sensor would only provide quantitative phase transformation measurements at one location i.e. only indicate one point on the transformation curve predicted by the mill models. In comparison, a number of sensors at different locations would provide a number of points on the transformation curve. This demonstrates the advantage of a sensor array for the Transformation Monitor system. The location of each individual sensor within the ROT should also be considered. Within a given product mix, steel grades will have a range of final structure property targets and therefore a range of compositions, rolling schedules and cooling strategies. This effects the number and optimum position if the sensor array. To demonstrate typical cooling strategies for 3 steel groups are reviewed.

4.1 Conventional Low Carbon Steels

These steels contain up to 0.1 wt. % C with typically 0.3 to 0.4 wt. % Mn and are hot and cold rolled to a finished product. With relatively low yield strengths (<300MPa) and high elongation, these steels are highly ductile and have excellent formability for cold deformed shapes. The microstructure of conventional low carbon strips is essentially ferrite and carbides; the carbides being in the form of either individual carbide particles or pearlite.

Figure 4a provides a schematic diagram illustrating a typical cooling strategy where a specific coiling temperature is targeted. Due to the low alloy composition, the transformation occurs at a temperature above the Curie point with more than 50% transformation expected by the time the transformation can be measured.

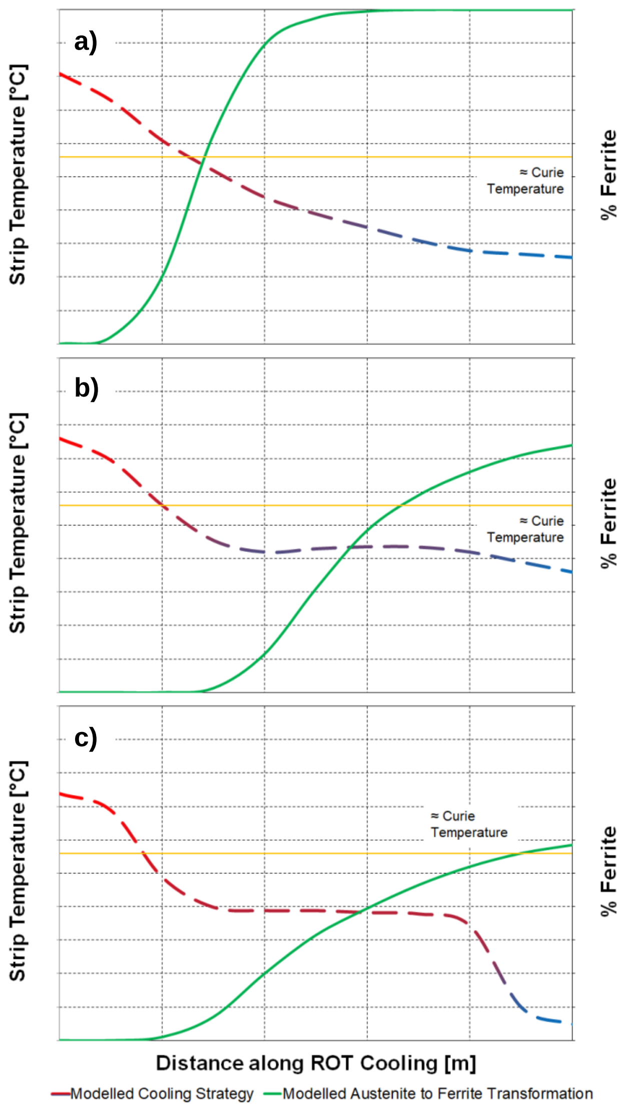

Figure 4. Comparison of cooling strategy and predicted transformation along the ROT cooling for 3 steel groups; a) conventional Low Carbon steels, b) conventional Structural steels and c) Advanced High Strength steel – Dual Phase (DP) steels.

4.2 Conventional Structural Steels

These steels generally have higher alloy contents than conventional low carbon steels, typically 0.15 to 0.25 wt. % C with up to 1.5 wt. % Mn. As a result they have higher yield strength but lower ductility and as a result are usually hot worked steels. Final mechanical properties are developed from the control of the chemistry and refinement of the grain size. These steels have a good combination of strength, ductility, toughness and weldability. Structural applications include pressure vessels, boilers and items for bridge and building constructions.

Figure 4b presents a schematic diagram showing a typical cooling strategy for a structural strip steel where similarly a coiling temperature is targeted. Due to the increase in alloy composition (C and Mn), the transformation from austenite to ferrite is delayed to lower temperatures, below the Curie temperature. In this example the early cooling strategy is followed by a period of air cooling on the ROT. The latent heat from the austenite to ferrite is transformation is shown by a slight increase in temperature on the ROT. Further cooling prior to coiling is expected from the trim section on the ROT cooling.

4.3 Dual Phase (DP) Steels

A ferrite – martensite dual-phase steel is a low to medium carbon steel with up to 50% volume fraction of dispersed martensite islands. Bainite and retained austenite can also exist. The ferrite phase is generally continuous giving these steels excellent formability whilst the hard second phase contributes to strength. The variations in potential microstructure give DP steels a wide range of strength and ductility. As such DP steels are known to be capable of absorbing large amounts of energy making DP steels highly desirable for automotive applications. When hot rolled, the rolling temperatures and cooling strategy are carefully controlled to produce the ferrite – martensite structure from austenite. The Transformation Monitor can measure the austenite to ferrite transformation for DP steels to monitor the final ferrite – martensite phase balance.

Figure 4c provides a schematic diagram showing a typical cooling strategy for DP steel. Similar to the example for the structural steel, a further increase in alloy complexity (high Mn), leads to the austenite to ferrite transformation occurring at temperatures below the Curie temperature. In this example the cooling strategy has two stages; initial intense early cooling stage where the strip is cooled to allow the formation of fine ferrite grains. An intermediate air cool is followed by a second cooling stage which is designed to achieve the right coiling temperature to develop the target ferrite – martensite (austenite at high temperature) dual phase.

4.4. EM Sensor Locations

A single EM sensor would only provide a single point of the transformation curves shown in Figure 4. Therefore an array of sensors is required. Figure 5 replicates Figure 4 but also includes example locations for an array of 3 EM sensors in the ROT. The EM sensor positions shown could represent the initial design for a sensor array with a view that they would capture important stages in the phase transformation. For example:

- EM1) To measure after early cooling.
- EM2) To measure prior to late cooling.
- EM3) To measure prior to coiling.

The 3 sensor locations shown in Figure 5 will provide 3 points to compare the measured phase transformation with that predicted from the offline or online physical thermodynamic and kinetic phase transformation models.

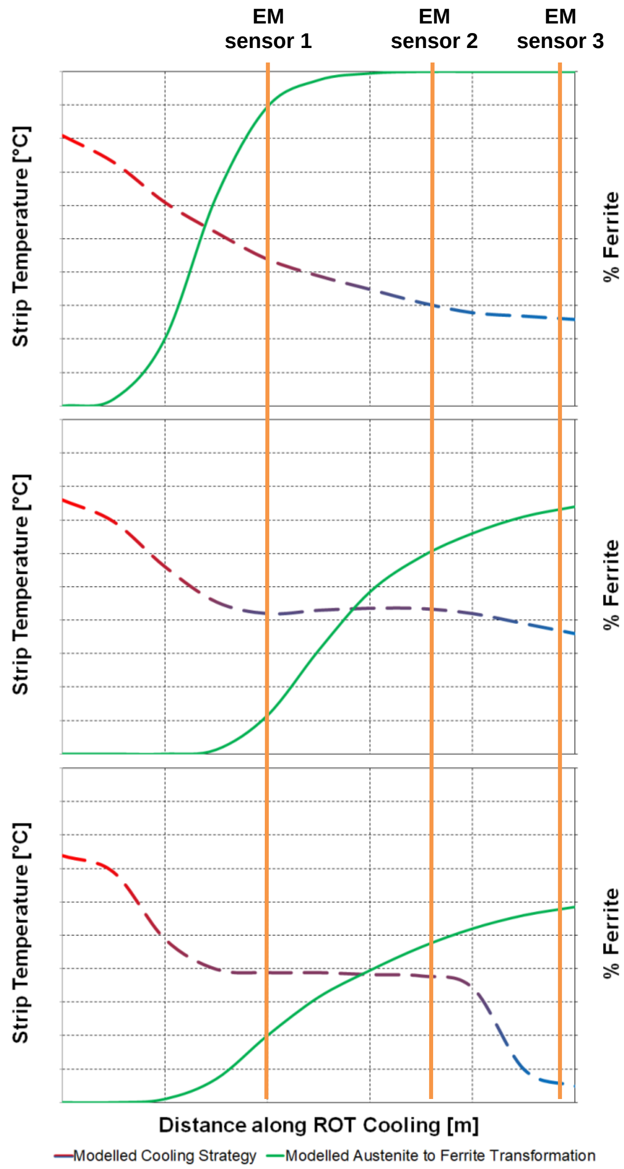

Figure 5. An update of Figure 4 with an example of 3 locations for 3 Transformation Monitor EM Sensors in the ROT.

For the example of conventional Low Carbon steels, the austenite to ferrite transformation is largely complete by the time the strip reaches EM1 and 100% complete by EM2 and EM3. Due to the relatively simple composition and final end use, the transformation of these grades is well understood. It is possible to consider further metallurgical information that can be obtained from the Transformation Monitor fingerprint of the strip as it passes each sensor. Factors that would influence the consistency and repeatability of the EM sensor signal from strip to strip include ferrite grain size and texture etc. [14].

For the conventional Structural steels and DP steels all 3 sensor locations shown in Figure 5 will provide measurements on the transformation curve. Due to increased alloying levels and a more intensive early cooling strategy, EM1 should provide a measurement point within the first half of the transformation curve. In addition EM2 and EM3 will measure the transformation at key points in the development of the final microstructure. In the case the Structural steels, before pearlite formation is expected whilst for the DP steels prior to late cooling and at the coiler where the percentage of ferrite prior to the formation of martensite is critical for process and final product consistency.

4.5. Practical Considerations

In Section 3, the two fold development of the Transformation Monitor was described. The first aspect was the robust industrialization of the EM sensors and the Transformation Monitor system whilst the second was the continued development and validation of 3D FE models used to improve the physical interpretation of the EM sensor signals.

Earlier in this section a description of a comparison between Transformation Monitor measurements of ferrite phase fraction and simulation results from inline metallurgical models was provided (see Figure 5). In order to ensure that the comparison between the results is reasonable some practical aspects of industrial rolling and modelling should be noted.

For the inline metallurgical models:

- Strip temperature deviations from the predicted (or expected) used to simulate the phase transformation i.e. the actual strip is hotter or colder which leads to more or less transformation.
- Strip positional errors relating to the accuracy of the tracking system i.e.

the modelled transformation is offset from the measured.

For the Transformation Monitor:

- For the 1st generation system, temperature is a required input. A pyrometer alongside the sensor can be affected by surface quality (scale) and cooling water carryover.
- The 1st generation system considers austenite to ferrite transformations only where the ferrite is polygonal ferrite formed by diffusive transformation. It does not include models for the transformations at higher cooling rates; e.g. austenite to bainite or austenite to martensite. If these morphologies are present they will influence the sensor signal, i.e. the EM sensors will 'see' them but currently their effect cannot be quantified.

5 CONCLUSIONS

EM based sensor technology can be used to detect changes in the magnetic behavior of steel. One emerging high temperature application is the novel Transformation Monitor system. This employs EMspec™ technology as part of an array of sensors located in the ROT during the production of steel strip. The system measures the austenite to ferrite transformation and records a "fingerprint" signal for each strip. This provides real time in-line microstructure measurements which can be compared to the thermodynamic and kinetic phase transformation models. As each sensor provides a measurement at a discrete position, the location should be considered prior to installation. Examples for different steel groups highlight how locations could be targeted to maximize the transformation information for specific high value grades.

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