In-Line Quantitative Measurement of Transformed Phase Fraction by EM Sensors during Controlled Cooling on the Run-Out Table of a Hot Strip Mill

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Abstract. In order to achieve the customer-required microstructure and mechanical properties of hot-rolled steel strip, the cooling process on the run-out table in a hot strip mill is dynamically controlled to optimize the temperature and phase transformation trajectories. The current practice is to feed a run-out table temperature control model with strip temperatures which are measured inline by optical pyrometers. However for advanced microstructure control, pyrometers alone cannot deliver an accurate state of the material. For proper control of the microstructure of the strip, in-line measured data of the amount of phase transformation are required as additional and/or alternative inputs to the process control model. This applies especially for high alloyed steel types. For this measurement electromagnetic (EM) sensors are a cost-effective option and will be considered in this paper.

It has been well known for a long time that during the cooling process, EM sensors are capable of probing the metallurgical phase change from austenite, being paramagnetic, to ferrite, being ferromagnetic below the Curie temperature. However, a quantitative measurement of the in-situ ferrite phase fraction by EM sensors at high temperature and in harsh industrial environments has been far from mature until recently. The major challenges are embodied in two aspects: how to condition the sensing devices in order to survive the harsh environments, and how to calibrate the measurement to the steel’s phase composition.

In this paper, we describe the working principle and the construction of an industrialized sensor system based on the measurement of the impedance-spectrum, which is now deployed in-line on the run-out table of the hot strip mill #2 at Tata Steel in The Netherlands. We will present how we succeeded in measuring transformed ferrite-phase fractions in industrial conditions taking into account alloy content and temperature. We will demonstrate the measurement performance, by comparing the in-line measured results with predicted values delivered by physically-based thermodynamic and metallurgical phase transformation mill models.
1. Introduction

A typical hot rolling process is schematically illustrated in Fig. 1. A slab is first reheated to the desired temperature in a furnace, enters a rougher mill and a multi-stand finish mill for thickness reduction, and subsequently the hot rolled strip goes through a forced-cooling process on the run-out table (ROT) before coiling [1]. The primary goal of a hot strip mill in the steel manufacturing route is to produce steel strips that have certain geometry, microstructure and mechanical properties required by customers, where mechanical properties are directly related to microstructure.

![Fig. 1 A schematic drawing of a hot rolling process in a hot strip mill. An EM sensor array system is installed along the ROT cooling zone to measure the amount of transformed phase fraction from austenite to ferrite.](image)

Manipulation of microstructure requires a careful control over the phase transformation kinetics in the whole process chain: alloy content, deformation during processing, austenite state prior to the transformation, the presence of precipitates and heat treatment [2]. The mechanical properties are improved mainly by adding alloying elements and heat treatment control, in which the latter one becomes more and more important. Given certain alloy content, the cooling trajectory and associated phase transformation on the ROT are crucial to the microstructure that determines the mechanical properties of the steel product.

The current practice for dynamic ROT cooling control is to feed a ROT temperature control model with strip temperatures which are measured inline by optical pyrometers. During the cooling process, steel strip experiences phase transformations from austenite to ferrite or other phases. The evolution of microstructure on the ROT is often predicted by thermodynamic and phase transformation models, because the accurate state of the material cannot be deduced solely from temperature information from pyrometers. However, these models are often empirical in nature and accurate prediction by these models requires thorough knowledge of the physical parameters governing the austenite decomposition. In addition, these models are often constrained by insufficient or inaccurate information on process and material conditions. These present shortcomings underline the need for an in-line measurement device that is able to sense the change of the microstructure, particularly the quantitative amount of transformed phase.

For the in-line measurement of phase transformation, non-contact electromagnetic (EM) sensors are advantageous compared to other techniques such as X-rays and laser-induced ultrasonics. They are also low cost for construction and deployment, have a fast response, are unaffected by water and oxide scales, and have no hazards to health and safety [3].

Our devices use electromagnetic principles to sense the metallurgical phase change from austenite, being paramagnetic, to ferrite, being ferromagnetic below the Curie temperature [4][5]. Although the sensing principle is well known for a long time, a quantitative measurement of the in-situ ferrite phase fraction at high temperature and in harsh industrial environments has been far from mature until recently. The major challenges are embodied in two aspects: how to protect the sensing devices in order to survive the harsh production environments, and how to calibrate the measurement to the steel’s phase composition.

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In this paper, we first present electromagnetic properties of steel that are relevant in the present context, prior to the description of an industrialized EM sensor system, which is now in-line deployed on the ROT of the hot strip mill #2 at Tata Steel in The Netherlands. Afterwards, we will illustrate the measurement procedure and demonstrate the in-line measurement performance by comparing the real-time measured phase fractions with predictions based on thermodynamic and metallurgical phase transformation mill models [6].

2. Electromagnetic properties of steel

Electromagnetic properties of steel vary over alloy content, microstructure, phase composition, temperature and heat treatment history [4][5]. Dependencies of EM properties on these aspects are often intrinsically related to each other. For instance, an increase in alloy content results in a decrease of the ferrite grain size, which leads to increased pinning of the magnetic walls by the grain boundaries. As a consequence, magnetic saturation and magnetic permeability are reduced; magnetic coercivity and electrical resistivity are increased. Magnetic properties are strongly related to microstructure, including grain size, inclusion content, carbide and nitride precipitates, dislocation density, phase balance and grain orientation. Grain boundaries as well as dislocations are known to be strong pinning sites for the domain walls. For small grains, each grain is one magnetic domain, while for large grains several magnetic domains can be accommodated within a single grain. Dislocation tangles/cells give rise to micron-sized substructures within the ferrite grain structure. Such a refinement has similar consequences as a decrease of grain size, i.e. work hardening and decreasing domain wall mobility.

In this paper, we are particularly interested in the variation of steel’s electrical resistivity and relative initial magnetic permeability, as these affect the EM sensor used in this work. The specific electrical resistivity is defined as the voltage / current ratio for a piece of material with unit length and cross section. In Fig. 2(a) we have reproduced the resistivity values for the pure iron and C-Mn steels reported in [7]. Resistivity increases steadily with the amount of alloy content and it has a strong dependency on temperature.

![Figure 2](image-url)

**Fig. 2** (a) Effect of alloy content and temperature on electrical resistivity of pure iron, C-Mn steels values (reproduced from [7]); (b) Temperature dependency of relative initial magnetic permeability (reproduced from [4]).
Relative magnetic permeability is defined as the ratio of magnetic induction and (applied) magnetic field. For ferromagnetic materials this “constant” depends on the applied magnetic field intensity. For the sensors used in this work, the magnetic permeability is considered to be the permeability determined from an un-magnetised or de-magnetised sample at low applied field, which is similar to the “initial permeability”.

During the cooling process of steel, austenite-ferrite phase transformation may start above or below the Curie point, depending on alloy content and cooling rate. With controlled cooling in a hot mill, most steel grades are forced to start transformation below the Curie point, which makes it possible to use magnetic sensors to measure the amount of transformed austenite phase. For the ferromagnetic status below the Curie point, magnetic properties are temperature dependent. Fig. 2(b) gives the temperature dependency of relative initial permeability that is reproduced from [4]. The peak in the permeability just below the Curie point is known as the Hopkinson effect, reflecting the fact that both magnetisation and magnetic anisotropy play a role in the temperature dependency.

3. Working principle and industrialisation of an EM sensor system

In order to measure austenite-ferrite phase transformation in real time, an electromagnetic sensor system, named as EMspec, has been developed by the University of Manchester in close collaboration with Tata Steel Research and Development [8][9]. After a successful trial for the proof of principle, Primetals Technologies (formally Siemens Metals Technologies) has joined forces to industrialize the sensor system [10][11].

A schematic drawing of the sensor is given in Fig. 3(a). Each sensor consists of an “H”-core yoke, an excitation coil, two active sensing coils and two dummy coils. The excitation of the sensor runs simultaneously at multiple frequencies in the range 0.2 – 50 kHz. The pair of active coils senses the voltage induced by a steel strip, while the dummy coils are used as a reference to compensate imperfections in electrical components and circuits. A digital signal processor (DSP) calculates the inductance spectrum based on a fast Fourier transform of the measured excitation current and induced voltage.

![Sensor head and magnetic loop](image1)

![An industrial sensor house](image2)

Fig. 3 The inductance sensor head consists of ferrite yoke, excitation coil and pick-up coils (a); it is assembled in a water-filled steel house with a ceramic window (b).
The measurement principle of the device is first to determine magnetic permeability from the zero-crossing frequency (ZCF) of an inductance spectrum, defined as the frequency at which the inductance goes to zero, measured by the sensor [8][9]. To deduce the ZCF, the inductance phase spectrum is used instead of the magnitude spectrum, because the phase is much less sensitive to the lift-off distance between the sensor and the target strip [12]. Theoretical model approaches show that for a ferromagnetic material, the ZCF is linearly related to the product of electrical resistivity and magnetic permeability [8]. With relative permeability determined from the ZCF, the amount of transformed austenite phase can be quantitatively calculated based on an effective medium model for a two-phase mixture of austenite and ferrite [13].

For in-line measurement, the sensors are located between transport rolls below the pass line of moving hot strips. Hot strips have a temperature in the wide range 500 – 800 °C during the cooling process and move at speeds up to 20 m/s. In order to survive the harsh industrial environment, each sensor is assembled in a steel house which has a ceramic window on the top and is water cooled at the side walls (see Fig. 3(b)). The industrial housing has been carefully designed to meet these challenging requirements at the same time: a compact design to meet stringent space constraints, a robust structure to survive severe mechanical vibration and thermal shocking condition, electromagnetic shielding against unwanted interferences in the production environment, and meanwhile electromagnetic transparency for the sensing of hot steel above the sensor.

4. In-line deployment and measurement results

Three EMspec sensors have been installed on the run-out table of the hot strip mill #2 at Tata Steel in The Netherlands, as schematically shown in Fig. 4. They are installed at three locations where pyrometers are present: the first two sensors are at the intermediate positions ET1 and ET2, the third one at the coiling position. It is expected that the amount of transformed austenite phase measured by the EMspec sensors together with the temperature delivers a more accurate description of the state of the material at these locations. In the next paragraphs, we detail the measurement procedure and evaluate its measurement performance.

![Fig. 4 Three sensors are installed on the run-out table at intermediate temperature positions ET1 and ET2, and the coiling temperature (CT) position in the HSM#2 in Tata Steel in The Netherlands](image-url)
For the purpose of demonstration, we first take a look at raw sensor data from a sample steel strip. This is a plain carbon steel with a thickness of 2.4 mm; the main alloy contents are carbon and manganese: C = 0.16 wt% and Mn = 1.00 wt%. The strip speed on the ROT varies in the range of 10 – 15 m/s from the head to the tail. Strip temperatures measured by pyrometers at the 3 locations are shown in Fig. 5(a). Note that the strip has a hotter tail than the body, which is achieved intentionally by cooling control in order to achieve a relatively uniform temperature distribution after coiling. From complex inductance spectra measured by the EM sensors the ZCFs are determined and presented in Fig. 5(b).

For a quantitative measurement of phase transformation, the relative magnetic permeability values are first deduced from the ZCFs and then translated to the amount of transformed phase fraction from austenite to ferrite in real time. Both the effects of alloy content and temperature on electrical and magnetic properties are corrected to ensure the measurement accuracy. The measured phase fractions for this strip are presented as dashed lines with circular markers in Fig. 5(c).

In order to evaluate the measurement performance, the measured values are compared with predictions, presented as solid lines in Fig. 5(c), based on process data using a physically-based thermodynamic and metallurgical phase transformation mill model [6]. There is clearly a strong agreement between the measured and predicted values in both trend and level, especially for the body part of the strip.

![Graphs showing strip temperature, ZCF, and phase fraction](image)

Fig. 5 For a 2.4-mm thick strip: (a) measured temperatures; (b) the ZCFs measured by the EM sensors; (c) measured and model predicted phase fractions at the ET1, ET2 and CT locations.
Table 1 lists the values at one typical location within the strip body (L = 289 m) and one near the tail (L = 850 m). For the body part of the strip, the difference between measurement and prediction is within ±5%. For the tail part the model predicts much lower phase fractions than the measurement. We have observed that such a deviation between measurement and model prediction at the tail of a strip happens occasionally, and these cases are under investigation.

<table>
<thead>
<tr>
<th>Positions</th>
<th>L = 289 m</th>
<th>L = 850 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strip temperature (°C)</td>
<td>ET1</td>
<td>ET2</td>
</tr>
<tr>
<td></td>
<td>722</td>
<td>707</td>
</tr>
<tr>
<td>Zero-crossing frequency (kHz)</td>
<td>2.53</td>
<td>12.54</td>
</tr>
<tr>
<td>Measured %Transformed</td>
<td>38%</td>
<td>64%</td>
</tr>
<tr>
<td>Predicted %Transformed</td>
<td>41%</td>
<td>64%</td>
</tr>
</tbody>
</table>

For the same steel grade we have examined many strips with thickness in the range of 2 – 5 mm, some of which are presented in Fig. 6(a)-(d), displaying good agreement between measurement and model predictions. These results show convincing performance of the EM sensors for the in-line and real time quantitative measurement of phase transformation in terms of accuracy and consistency.

![Graphs showing phase transformation](image)

**Fig. 6** Measured and predicted percentage of transformed phase fractions for 4 steel strips with increasing thickness; measurements are presented by dashed lines with circular markers, predictions by solid lines.
5. Conclusions

In this paper we have described an industrialized electromagnetic sensor array system, which is deployed on the run-out table of the hot strip mill #2 at Tata Steel in The Netherlands, for in-line real-time measurement of the amount of transformed phase fractions from austenite to ferrite during the cooling process. The sensor array has been running in the high temperature and harsh production environment for a year.

For a quantitative measurement of phase transformation, the effects of alloy content and temperature on electromagnetic properties were carefully modelled and taken into account during the calibration procedure. The measurement performance is evaluated for a steel grade by comparing the results with model predictions delivered by a physically-based thermodynamic and metallurgical phase transformation mill model. For many strips with thickness in the range 2 – 5 mm, the measured and predicted results show a strong agreement in both trend and level, especially for the strip body. This has successfully demonstrated that the EM sensor system is able to quantitatively measure phase transformation in an accurate and consistent manner as long as it is well calibrated.

Further work will focus on application of this technology to novel high strength steel grades with multi-phase microstructures.

References