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ON-LINE PHASE TRANSFORMATION MONITORING ON A HOT STRIP MILL*

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Abstract

The EMSpec sensor employs the principle of measuring the complex impedance of the target steel over a range of frequencies these impedance values in turn varies with transformation fraction of the steel. A full scale implementation of the Real Time Transformation Monitoring has been installed at a quality large European steel producer to show the benefits of such a system. A total of three EMSpec sensor heads have been installed between the exit Finishing Mill and the Down Coiler on a HSM. For the successful production of Dual Phase, TRIP and TWIP steels increased control of the cooling regime is demanded; the use of surface temperature measurements alone cannot guarantee to achieve the desired mechanical properties. The EMSpec sensor, which is engineered to withstand this harsh environment, in real time directly measures the percentage transformation of the steel in the cooling area, typically in the accelerated water cooling zone. Using the information from the sensors integrated into the mill model enhances the models ability to predict the transformation profile.

Keywords: Transformation monitor; Microstructure measurement; Dual phase steel; Hot strip mill.

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1 INTRODUCTION

There has been a strong requirement for many years to develop a sensor that can detect in real time the change of steel properties as it transforms from the Austenite state. Research has been undertaken for many years at both Manchester and Birmingham Universities in the UK [3, 8, 9] to exploit the changing magnetic properties of the transforming steel by use of an Electromagnetic Sensor (EMspec® Technology from Manchester University). By measuring the magnetic permeability of the steel as it changes from paramagnetic to ferromagnetic a measure of the percentage transformation of the steel can be calculated. This principle is well known but signals from simple sensors are affected by distance from the target material which is unacceptable for an online sensor. Research at Manchester University has looked into the effects of magnetic permeability with respect to frequency of the applied sensor excitation. Combining the effects of the phase transformation and frequency on the permeability a sensor head was developed using a spectrum of excitation frequencies (see Figure 1). For each frequency the complex impedance can be measured by the sensor and presented as a phase diagram on a polar plot (see Figure 2). By normalising the sensor on a paramagnetic sample the vectors of the impedance rotate around the polar plot as the material transforms with the higher frequencies rotating the most. As mentioned with a simple sensor the magnitude of the measured signal varies with standoff from the target but in the case of the spectrum of frequencies the phase angle of the complex impedance is relatively immune to standoff variation only the magnitude of the vector changes. By analysing the phase angles of the measured complex impedance a measurement can be calculated of the percentage transformation of the steel. This gives this sensor and the way the signals are analysed its unique properties making it suitable to progress for site trails to online conditions.

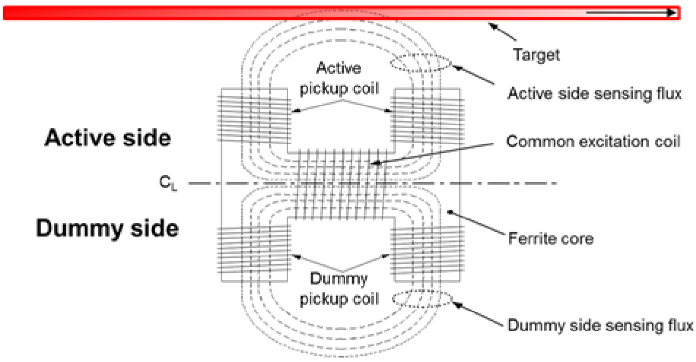

Figure 1. Schemeatic of Sensor Head

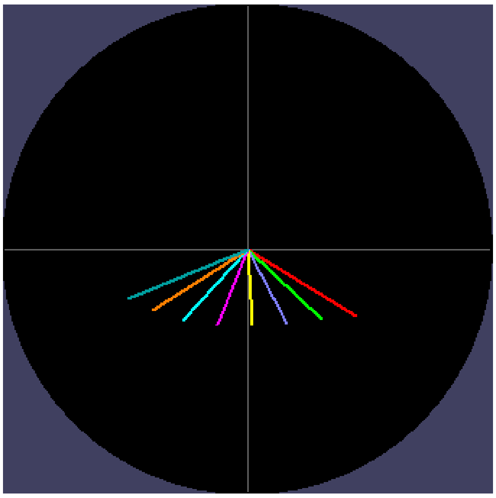

Figure 2. Basic Polar Plot

The University of Manchester conducted early work with Tata Steel at three sites in northern Europe (Port Talbot and Scunthorpe in the UK and IJmuiden in Holland) which proved the value of the sensor and obtained a detailed insight into the robustness of the sensor in the conditions presented by the hot steel production environment. Latterly, Primetals Technologies (formally Siemens Metals Technologies), have been pivotal in developing and supplying the industrial sensor,

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processing electronics and software. Following on from the initial trials, with the three sensors located alongside existing pyrometers to measure the transformation from the exit of the finishing mill to the down coiler.

2 ENGINEERING THE SENSOR

To ensure the sensor gives a reliable consistent measurement in the harsh Run Out Table (ROT) environment it is essential that the sensor is well engineered. The sensor ferrite core is an H shape and the poles of the H have to be within 50mm of the target material.
To integrate the sensor into the Run Out Table its best position is to be mounted beneath the strip and between rolls. This minimises any modifications to the roller table as it can be mounted alongside a pyrometer installation. The sensor itself is relatively small only 250x140x30mm (see Figure 4).

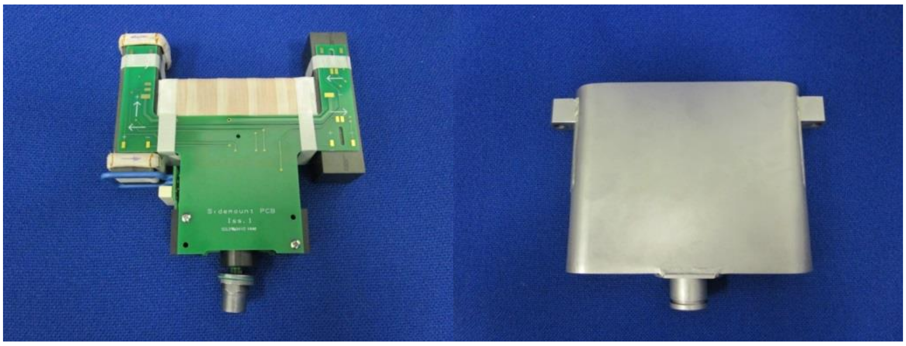

Figure 3 Primetals Industrialised sensor & Container

The sensor itself is mounted into an environmental housing which protects the sensor from heat, strip impact and locates it in the correct position. The housing is designed to fit between specific roll gaps, in the case of Tata Steel IJmuiden this is 74mm which is probably the closest roll spacing of most Hot Strip mill run out tables. For other mills, the housing will vary using parametric to adjust the size to fit between the rolls but the sensor module will be a standard unit (see Figure 4).

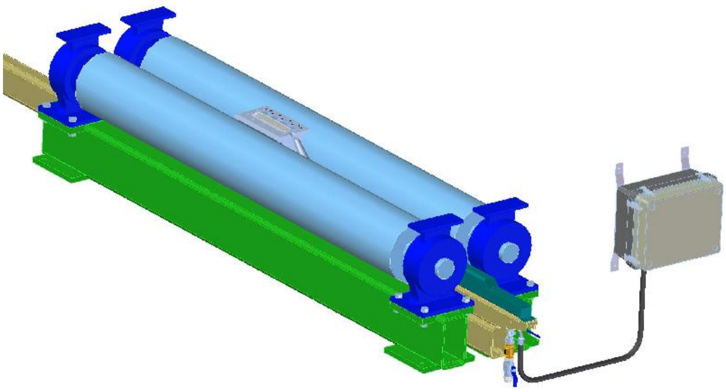

Figure 4 Sensor Container & Housing and mill location

The sensor housing provides a water jacket for the sensor and is designed to provide a laminar flow around the sensor using mill cooling water at 10l/min. The housing is capped off with a cover which is just below the mill pass line. The cover acts as the mechanical protection for the sensor and can be prone to damage in the case of extreme strip breaks and ‘mill wrecks’, so is easily exchangeable. The cover has a high temperature glass ceramic aperture, necessary for the electro-magnet field to pass through which is sufficiently tough to with stand most impacts. The cover is used for the exit of the cooling water to wash on the cover to prevent the build-up of oxide residue. All the remaining components for the housing are made from stainless steel.

By using this modular design the sensor and housing can be easily maintained in this difficult environment with a removable cover and simple plug in sensor.

3 OPERATIONAL ASPECTS

An array of sensors along the Run out Table from Finishing Mill to Down Coiler is preferred. This allows a measurement of the trend of transformation in the cooling zone rather than at a single fixed point. Also using an array of sensors a relative measurement between the sensors could be just as usable as absolute results from each one where the trend of the transformation is usable.

A typical installation would use a minimum of three sensors; these would be located after the controlled cooling zones (typically where a pyrometer is located) and finally at the entrance to the down coiler. These would be mounted on the centre line of the Run out Table for a standard Hot Mill installation. For wider material (plate mill applications) additional sensors would be mounted across the roller table, nominally spaced 500mm apart, forming a matrix of sensors. This would measure the transformation variation across the width which would allow for better microstructural control from centre to edge. Currently the system is configured to accept a maximum of sixteen sensors (see Figure 5).

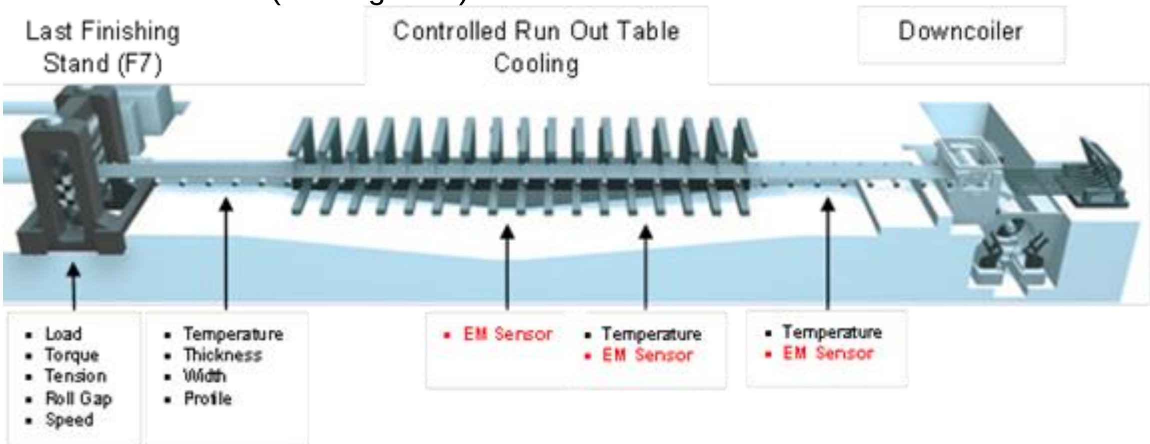

Figure 5. A schematic diagram to show the typical instrumentation towards the end of processing on a Hot Strip Mill and the proposed locations of the sensor using EMspec® technology for forthcoming Industrial Trials

The sensor design for the hot strip mill has the pole spacing across the H of 120mm. With this configuration the sensor penetrates the steel to a depth of 5-10mm (see Figure 6) which is suitable for most thicknesses rolled. For other thickness steels, especially for plate then an increase in pole spacing will be required to measure deeper into the material. However this moves into the area of through thickness transformation rates which is more complex than the simpler relatively thin material where this is largely negligible.

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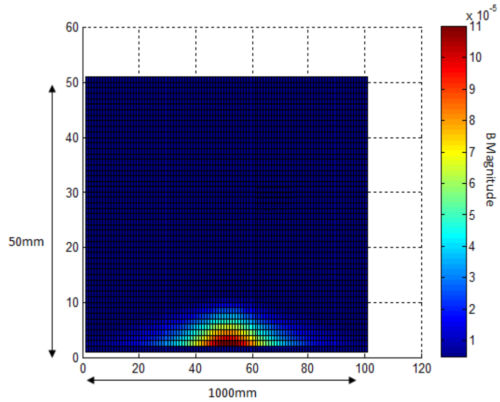

Figure 6 Example of FEM Model to calculate field penetration.

As mentioned the ideal Hot Mill configuration for the Transformation Monitor is to have an array of sensors mounted along the mill centre line between rollers below the pass line. This makes the sensors difficult to access during rolling operations so any normalisation or calibration needs to be performed remotely. Integrated into the head is a calibration load coil than can be energised remotely by the control system to provide a known result to adjust the output. This can be used to eliminate any drifting of the sensor due to temperature or aging. The process only takes a few seconds and can be easily performed between coils (even at high pace rolling rates) either triggered automatically or via operator command.
The basic system design includes the sensor head, conditioning PCB and processing PC. The conditioning PCB contains the high speed firmware running on the DSP to control the sensor, condition the output signal and calculate the complex impedance. Each sensor has its own PCB which is networked with other sensors to the main processing PC.
The main processing PC contains three applications plus a data logging package which can all run on one machine or distributed on many machines as long as they are on the same network. The applications are:
Head Controller EMspec® – this application controls and interfaces up to 16 separate heads (which will be sufficient for most installations). The application stores and downloads all the set up and configuration data and processes and monitors all the results. The application has many diagnostic features to monitor the performance of each sensor plus configuration genies and wizards to guide technicians through the set up procedure to ensure optimum performance from the sensor (see Figure 7).

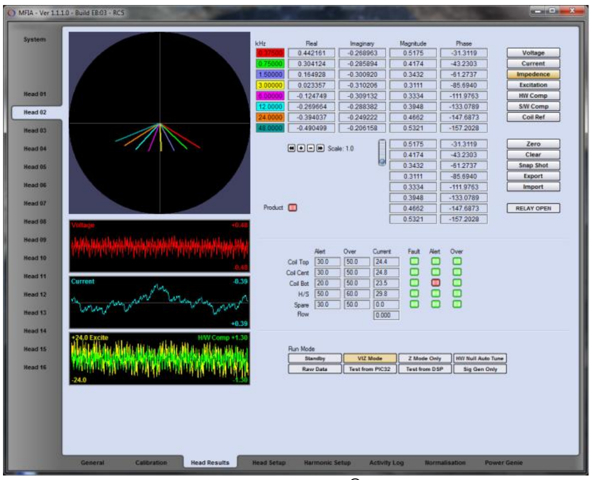

Figure 7 EMspec® software

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Data Server DJX – This is a server application which is the centre of the processing and interpretation of the complex impedance from each head. It communicates with both level 1 & 2 automation systems to receive all the necessary process information to calculate the transformation fraction at the point of measurement. The information necessary from level 2 needs to include alloy type and chemical makeup plus other process information. The results are then fed back, in real time to the cooling model for comparison to the predicted transformation profile along the run out table.

HMI – This is an option application to present the real time data to the operators to assist them in the monitoring of the process to ensure the steel is rolled and cooled to the correct microstructure. Numeric and graphical results are presented to the operator showing the percent transformation, compared to the predicted (if available) alongside temperature information.

Sprite Data Logger – This application records results and setup data in real time for either for diagnostics or replay purposes from the DJX server.

To take full advantage of the new real time measurement of Transformation fraction the mill model needs to be able to utilise the feedback information. Such models as the Microstructure Monitor and Cooling Model from Primetals Technologies (Formally Siemens MT) will be configured to accept the input but other externally available models will have to be restructured.

4 WHAT ARE THE MAIN ADVANTAGES TO USING A TRANSFORMATION MONITORING SYSTEM?

Whether using a single sensor or an array of sensors this real time measurement will give a better understanding of the cooling/transformation process which will ultimately achieve the desired microstructure and hence material properties. This can range from;

- The full integrated sensor providing direct feedback to the mill model and control system.
- The real time monitoring of the cooling process, to allow operator interventions.
- Post process analysis to allow investigation into the rolling process for improvement.
- The system will give a more consistent measurement of the transformation process which cannot be reliably achieved using conventional surface temperature pyrometers, especially when Dual phase, TRIP and TWIP products are being rolled.
- The development of mill models to economically roll advanced grades of steel will only be possible using this measurement.
- Yield savings that could be realised by improving the yield in high value steel production, whereby coils could be scrapped or downgraded when the desired microstructure is not achieved.
- The other potential large cost saving is the reduction of micro-alloying elements currently used to create the required microstructure. By using the Transformation Monitor system a better understanding and control of the process can be achieved. This now gives the opportunity to “Roll in” the desired material properties and rely less on micro-alloying.

5 RESULTS

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 Figure 9(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 zero-crossing frequencies (ZCFs) are determined and presented in Figure 9(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 dash-circle lines in Figure 9(c).
In order to evaluate the measurement performance, the measured values are compared with predictions, presented as solid lines in Figure 9(c), based on process data using a physically-based thermodynamic and metallurgical phase transformation 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. 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.

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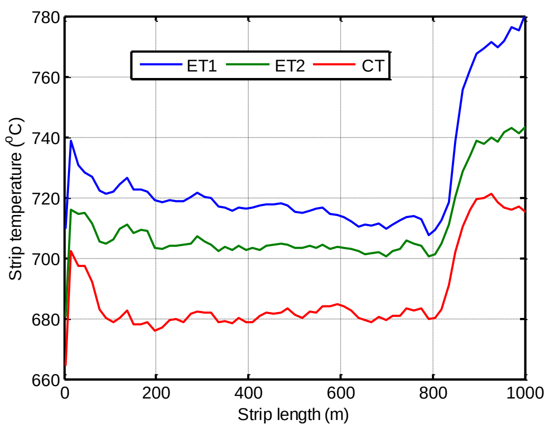
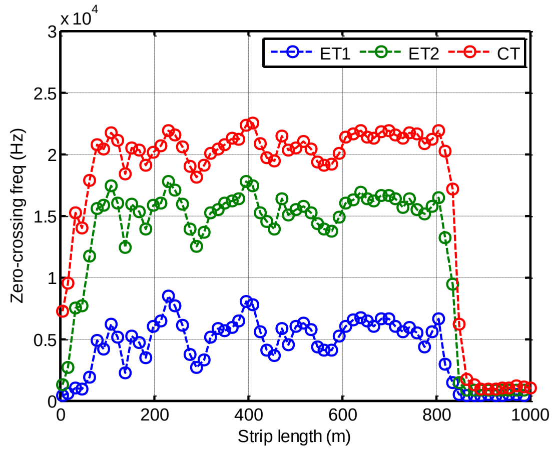
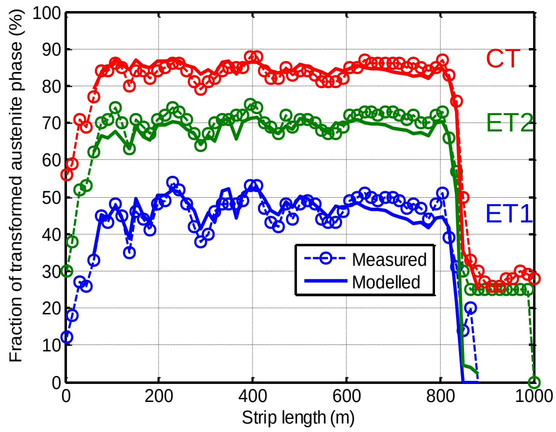


(a) Strip temperature



(b) ZCF



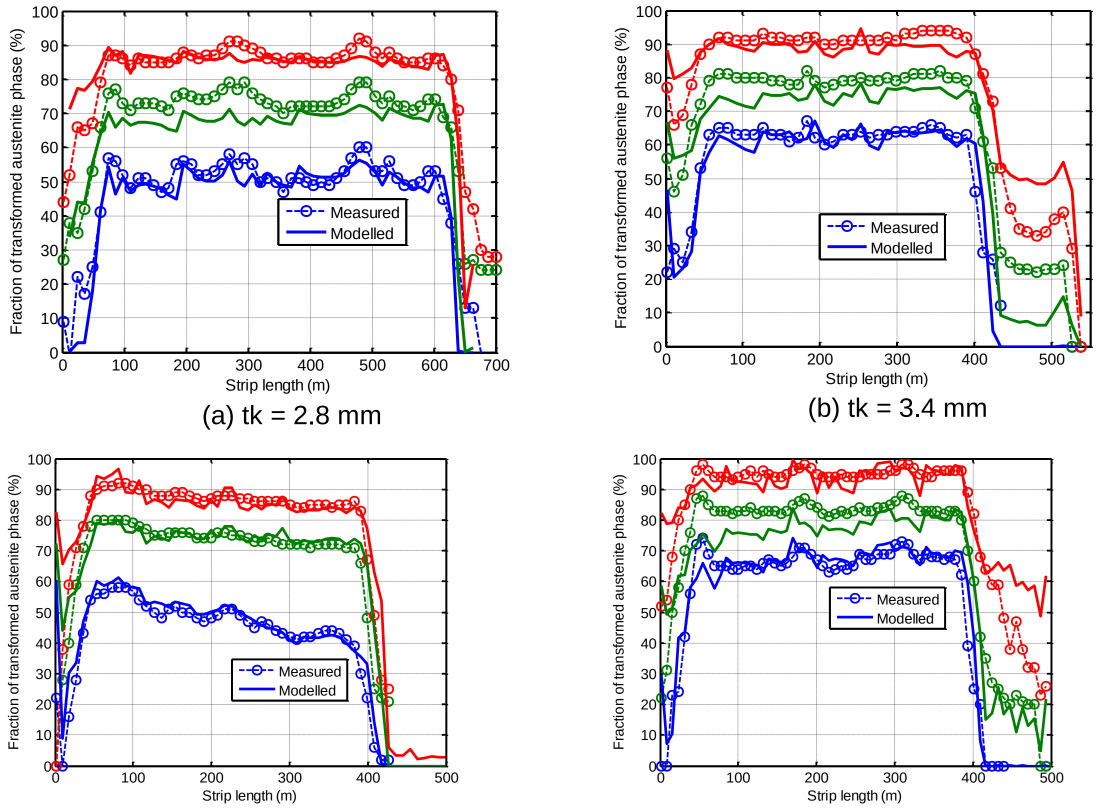
(c) Measured and predicted phase fraction

Figure 9 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 ET1, ET2 and CT locations.

Table 1 Measured and predicted amount of phase transformation at L = 289 and 850 m.

Positions	L = 289 m			L = 850 m		
	ET1	ET2	CT	ET1	ET2	CT
Temperature (°C)	722	707	682	738	720	702
Zero-crossing frequency (kHz)	2.53	12.54	17.70	0.47	1.32	6.18
Measured %Transformed	38%	64%	79%	14%	30%	50%
Predicted %Transformed	41%	64%	83%	0%	5%	35%

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 Figure 10(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.



(a) tk = 2.8 mm (b) tk = 3.4 mm (c) tk = 4.0 mm (d) tk = 4.5 mm

Figure 10 Sample strips with good agreement between measurement and predictions in the strip body.

6 CONCLUSION

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.

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