Section - IV

ELECTROMAGNETICS

Monitoring of Steel Microstructures using Electromagnetic Sensors

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ABSTRACT

The characterization of steel microstructures is an important tool for metallurgists as mechanical properties are controlled by microstructural parameters such as grain size, phase balance and precipitates. This paper describes multi-frequency electromagnetic (EM) sensors that have been designed to detect changes in the relative permeability and resistivity of steel on-line during steel processing, which can be directly related to changes in microstructure. Examples presented in this paper include both laboratory hot tests and industrial field trials for monitoring of phase transformation in steels, detection of decarburization on a steel rod surface, and imaging of molten steel in the submerged entry nozzle (SEN) during continuous casting.

Introduction

Steel microstructural analysis is typically carried out off-line using small samples, for example by optical microscopy, X-ray analysis, dilatometry, SEM or TEM. A significant advance in materials characterisation would be obtained if microstructural information could be determined, in a non-destructive and remote manner, e.g. on-line during steel production or in-situ for steel applications. One technique being developed is induction spectroscopy (IS), which uses the electromagnetic (EM) properties of steel to allow microstructural information to be determined. Electromagnetic sensors are sensitive to changes in the magnetic permeability (dominant effect) and electrical resistivity (minor effect) of the steel. The magnetic properties of steel are affected by the matrix microstructure: austenite is paramagnetic (relative permeability, μ_R of approx 1) whilst ferrite is ferromagnetic below the Curie temperature, T_c, ($\mu_R > 200$).

The EM sensor system used in this work allows changes in magnetic permeability and electrical resistivity within a steel sample to be detected and related to its microstructure [1-3]. Furthermore, the use of multiple frequencies allows information to be gathered which is indicative of the state of the steel at different depths from the surface due to the fact that higher frequency magnetic fields will penetrate less deeply than those of lower frequency. The system works by measuring changes in the real and imaginary inductance of an electromagnetic sensing head close to the steel sample. Essentially, a variation in imaginary component of the inductance relates to the variation in the actual energy loss element (i.e. the overall resistive component of the sensor head and target sample) whereas a variation in real component of the inductance relates to the energy storage element, (i.e. the inductive component).

This paper presents several examples of the application of EM sensors during on-line processing of steels. These include both laboratory hot tests (monitoring of phase transformation in a Fe2.25Cr1Mo steel and detection of decarburisation on a high carbon steel rod) and industrial field tests (monitoring of phase transformation in rods and imaging of molten steel).

Laboratory hot testing

An air-cored EM sensor was designed to perform testing at high temperatures such as within a furnace environment or for use with a hot sample (Fig. 1). The sensor was fabricated using thermocouple wires and ceramic slurry by investment casting. Both the exciting and sensing coils were embedded in a ceramic shell (white in Fig. 1) and have about 50 turns. Samples with a thermocouple attached (black in Fig. 1) were inserted into the sensor and tested in a furnace up to 1000°C. The samples were wrapped in austenitic stainless steel foil to minimise oxidation and decarburisation at high temperature. The EM sensors' exciting and sensing coils were driven using an impedance analyser (SL1260) at frequencies from 10Hz to 1MHz and measurements of real and imaginary inductances were taken for all samples. Simultaneously, the sample temperature was recorded. Using this high temperature sensor, a range of hot tests has been carried out to monitor the steel microstructure change at high temperature. Two examples are shown as follows.

Fig. 1: Photograph of an EM sensor (length 140 mm, inner diameter 20 mm) designed for high temperature use, in this case monitoring phase transformation in a steel rod sample during air cooling from 1000°C.

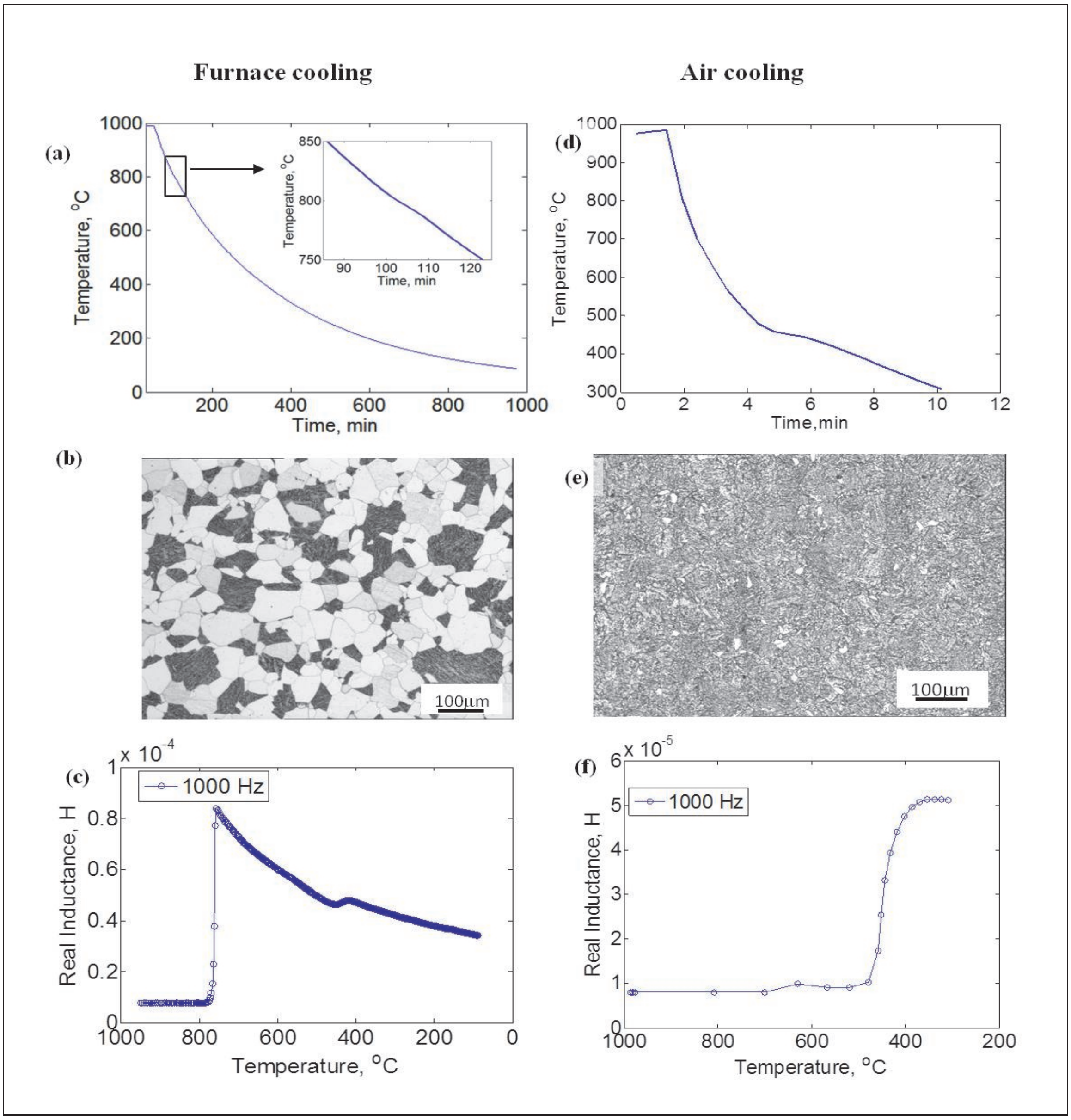

Fig. 2: Dynamic EM sensor test results during cooling from high temperature showing phase transformations in a Fe2.25Cr1Mo steel where the furnace cooling results are on the left and air cooling results on the right. (a) and (d) are the temperature-time curves, where the ferrite transformation can be seen as a slight change in slope in the inserted figure in (a). (b) and (e) show the microstructures after testing. The real inductance at 1000Hz indicates the difference in phase transformation between the furnace (c) and air (f) cooling conditions.

Phase transformation in Fe2.25Cr1Mo steel

Fe2.25Cr1Mo steel transforms from austenite to different microstructural phases during cooling from high temperature depending on the cooling rate: for the sample sizes investigated in this work furnace, cooling generates a ferrite+bainite microstructure while air cooling produces an almost fully bainite microstructure. This steel was used as it transforms at relatively low temperature (i.e. below the Curie temperature) to test the sensor's capability for monitoring the phase transformation dynamically. The dynamic EM sensor test results are shown in Fig. 2 (furnace cooled results on the left side and air cooled on the right side for comparison). For the furnace cooling, it can be seen the inductance signal increases sharply at 770 °C due to the presence of a large volume fraction of ferrite (> 30%) forming before the Curie temperature (Fig. 3). Below the Curie temperature, the real inductance value decreases due to the fact that the sample's electrical resistivity reduces as the temperature decreases so that the eddy current effect becomes stronger. At approx 450 °C, the real inductance signal increases again due to the formation of ferromagnetic bainitic phase from the remaining austenite (paramagnetic), and the bainitic transformation finishes by 410°C. This change in real inductance is relatively small despite there being approximately 20% bainite forming (figure 2(b)) as the permeability of bainite is smaller than that of ferrite, and it is known that the signal is dominated by a connected ferrite phase [5]. Whilst the cooling curve (Fig. 2(a)) shows only the ferritic transformation (seen as a small change in slope of the cooling curve), the EM sensor can detect both the ferritic and bainitic transformations. For the air cooling test, a very small signal change can be seen at approx 700 °C due to the formation of ferrite (<2% volume fraction as shown in Fig. 2(e)). The main inductance signal change occurs at approx 450 °C and is due to the formation of bainite, which can also be seen from the cooling curve (Fig. 2(d)). The start of the bainitic transformation occurs at 500°C and is complete by 380°C according to the inductance signal. The amount of ferrite/bainite formed at any point below the Curie temperature during the cooling cycle can be estimated from the inductance value and the relationship between inductance and transformation fraction determined experimentally or by modelling and discussed elsewhere [5]. These results clearly show that the sensor is capable of dynamically monitoring the phase transformation in steels below the Curie temperature.

Decarburisation on Fe-0.8C steel rod

During the high temperature processing of high carbon steels, decarburisation can occur resulting in a carbon depleted surface layer that is undesirable in the final steel product. EM sensors offer the potential for detecting and measuring the depth (via the multi-frequency approach) of a decarburised layer either on-line during processing (decarburised ferrite layer and untransformed austenite bulk) or off-line (e.g. decarburised ferrite layer and pearlite bulk). Previously simulated on-line measurements have been carried out using model microstructure samples comprised of an austenitic stainless steel core and surrounding tube of ferromagnetic ferritic steel of varying thickness [4]. It was shown that the EM sensor is capable of detecting the different ferrite layer thicknesses. With this new high temperature sensor, it is possible to measure real decarburized samples at high temperature. Figure 4(a) shows the measured real inductance (at 1000Hz) variation with temperature

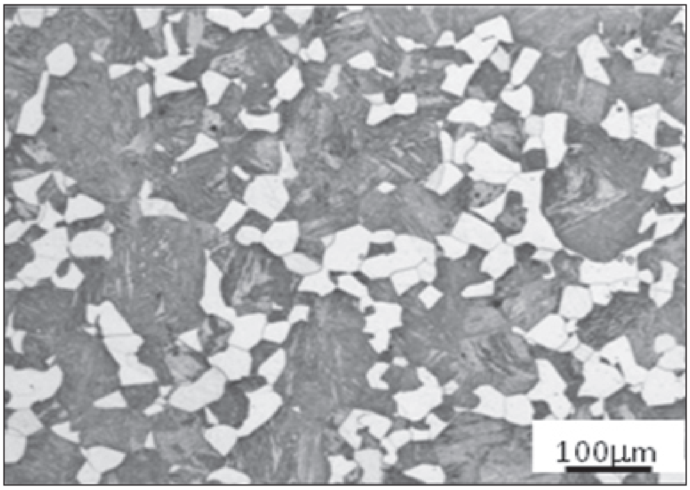

Fig. 3: Microstructure of Fe2.25Cr1Mo steel after austenisation at 1000 °C for 30 min followed by furnace cooling to 800 °C and then water quenching showing the formation of ferrite (white).

during air cooling of three Fe-0.8C wt% steel rods after decarburization treatment at 1000°C for different times. The sample decarburized for 15 min shows a flat inductance signal between 900°C and 700°C which indicates that no phase transformation occurs. Below 700°C, the inductance starts to increases and a big jump appears around 650°C (where the pearlitic transformation is expected for this cooling rate). After testing, the microstructure was examined and very little ferrite was found on the surface of this sample, with a fully pearlitic matrix being observed (Fig. 4(b)). This confirms that the significant increase in inductance value at around 650°C is due to the formation of the pearlite phase. The inductance signal of the sample decarburized for 1 hour is similar to that of the 15 min treated sample, although the inductance signal starts increasing at a higher temperature (730°C), which indicates some ferrite transformation around austenite grain boundaries in a partially decarburized surface layer (Fig. 4(c)). On increasing the decarburization time to 5 hours, the inductance shows a sharp jump around 760°C (Curie temperature) followed by a further slow increase before the pearlitic transformation. The inductance jump around the Curie temperature is due to the fully decarburized layer transforming to ferrite above the Curie temperature (Fig. 4(d)). The continuous ferrite layer forms an easy magnetic flux path which causes the large signal jump. The subsequent slow increase in inductance value with continued cooling is due to further ferrite transformation in the partially decarburized zone. These results show that a sensor installed at an appropriate position (at which the product's temperature is between the Curie temperature and the pearlitic transformation temperature) in a mill will be able to monitor decarburization in the products during processing. The development of EM sensors capable of being used within a furnace or similar environment for long time periods is on-going and offers the potential for a range of in-situ microstructural monitoring applications during high temperature processes.

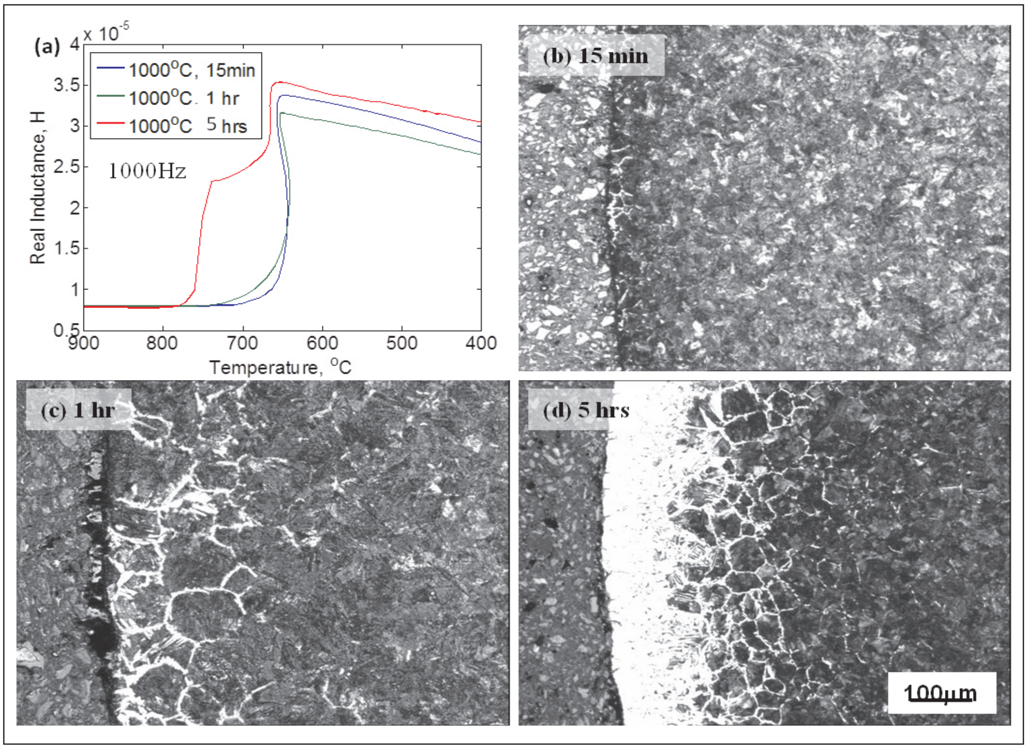

Fig. 4: Monitoring of decarburisation in Fe-0.8C steel rods during air cooling from high temperature: (a) the real inductance variation with temperature (a small increase in temperature is due to the recalescence of pearlitic transformation), and the microstructure near the surface of tested rods, which were decarburised at 1000 °C for (b) 15 min, (c) 1 hour and (d) 5 hours in the air furnace before cooling. The sample decarburised for 5 hours shows a large signal jump at around 760 °C, which is due to the presence of a decarburised ferrite layer that forms a continuous magnetic flux path.

Industrial field trails

Phase transformation in rods

A multi-frequency EM sensor has been installed at Tata Steel's Scunthorpe Rod Mill. Figure 5 (a) shows a schematic diagram of the run-out table on a typical rod mill with the main sections indicated; namely the laying head, conveyor, controlled cooling fans and enhanced cooling zone. Also illustrated is a schematic temperature versus distance curve for a high carbon steel. Possible locations for the sensors are indicated in order of priority, with the most important location (and the one used in the trial) being at the end of the enhanced cooling zones in order to detect whether full transformation has occurred. Whilst the steel may be at high temperatures (600-800°C) the EM sensor can be positioned at a lift-off of up to 100mm in a protective casing with water cooling, allowing for long term condition monitoring. For the field trials the sensor was mounted between the rollers at the end of the enhanced cooling zone. In this case, only whether transformation has occurred or not could be accurately determined as the magnitude of the inductance signals, which relates to the amount of transformation, is affected by lift-off. As a fixed lift-off from the sensor to the steel rod could not be maintained, the phase angle was measured, as this parameter has been shown to be lift-off insensitive [2]. Results are shown in Fig. 5(b), modified from reference [6]. The coils are a boron steel and it can be seen from the phase angle response that the leading few seconds of the coil are not fully transformed (a phase angle greater than 90°) but the remaining coil length has transformed, the desired microstructural state after the enhanced cooling zone. The untransformed leading edge of the coil results from a lack of water cooling prior to the conveyer, as water cooling may be delayed until the start of the strand has engaged with the laying head. Depending on the customer requirements, this part of the coil may be removed prior to shipment. The EM sensor can be used to confirm when the desired transformation has occurred and how much rod from the front end of the coil might need to be removed.

Imaging of molten steel

The control of steel flow through a submerged entry nozzle (SEN) during continuous casting is critical to ensure steel cleanness and surface quality. Electromagnetic induction tomography (EMT) techniques have been developed attempting to determine the steel flow patterns and detect clogging caused by alumina deposits within the SEN. Using EMT techniques, measurement can be obtained by energizing an excitation coil with an ac signal, hence creating a magnetic field. Electrically conductive or ferromagnetic objects in the vicinity cause the applied magnetic field to be modified and the resultant field changes are measured with an array of detection coils. If a series of excitation coils are energized sequentially around the object, it is possible to generate an image of the object based on a set of measurements through the utilization of suitable reconstruction software. Hot casting trails were undertaken at the Tata Teesside Technology Centre [7]. The sensor array was placed around a standard slab caster nozzle and connected to the EMT instrument through long thermal shielded cables. The test lasted around 20 s. During data logging, the steel flows were purposely controlled at different positions in the pouring nozzle, and flow patterns were also observed and recorded using video for comparison. Images of steel flow profiles are produced by applying simultaneous iterative reconstruction technique (SIRT) with a relaxation factor $\lambda = 5 \times 10^{-6}$, 20 iterations and non-negative constraining. A selection of results is shown in figure 6. The images are shown in sequence from left to right and then from top to bottom indicating the pouring of molten steel at different time instants. The first row in the figure shows the steel flow was initially positioned in the middle of the nozzle. The second and third rows show the steel flow then splashed the sidewalls of the nozzle. Images in the last row show the deposition of steel remnants on the inside of the nozzle wall after the pouring. It has found that EMT images were consistent with video recordings in terms of flow size and positions. Further development to monitor two-phase flow (molten steel and argon gas) in the SEN is undergoing [8].

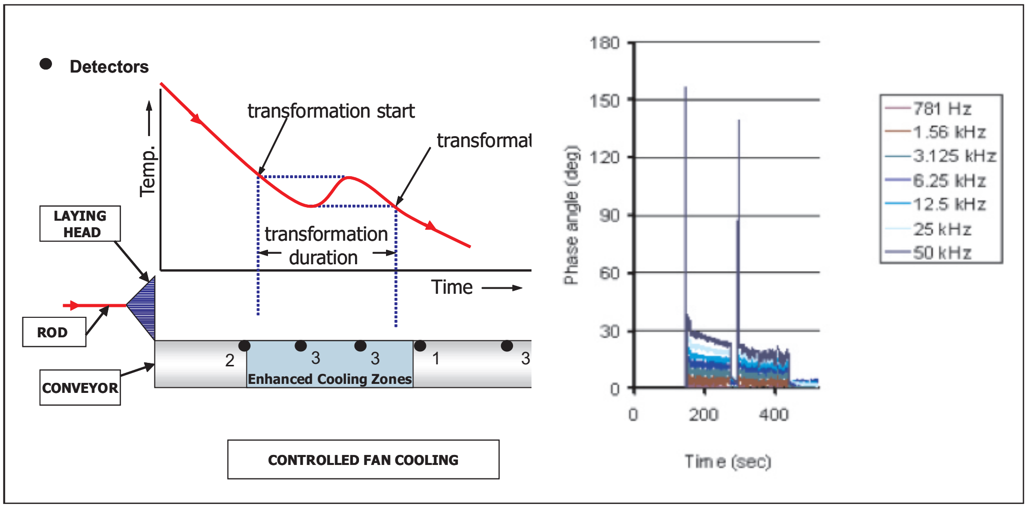

Fig. 5: (a) Outline schematic diagram of the run-out table on a typical rod mill and (b) phase angle response for two 12.5 mm diameter rod boron-steel coils. The leading few seconds of the coils are not fully transformed as indicated by a phase angle greater than 90º, modified from reference [5].

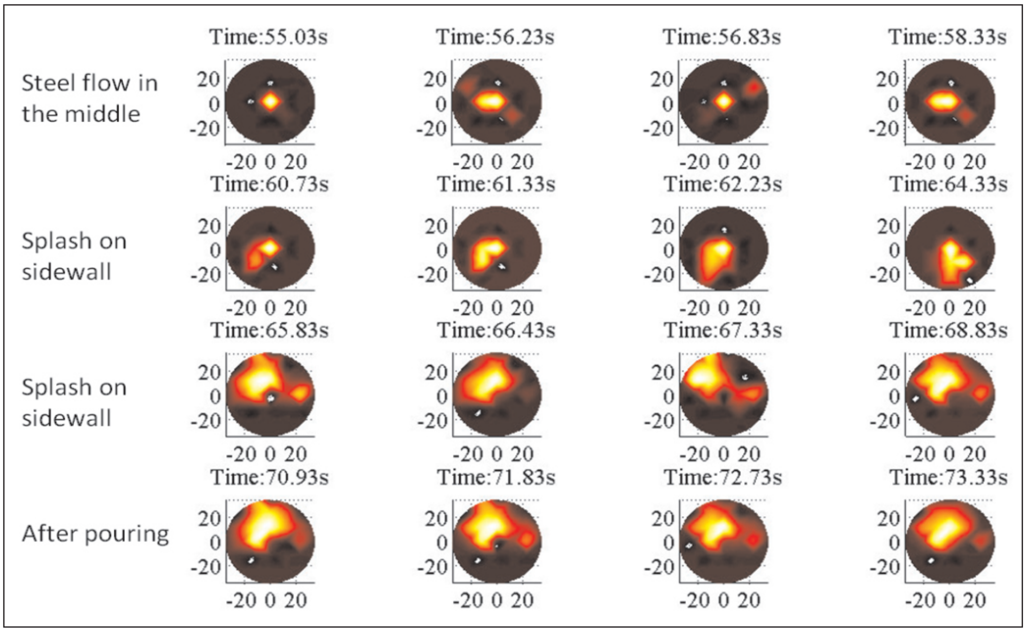

Fig. 6: Imaging of molten steel in a submerged entry nozzle during continuous casting [6].

Summary

EM sensors are sensitive to changes in the magnetic permeability and the electrical conductivity in steels. The electromagnetic properties can be linked to microstructure, temperature and spatial distribution of the steel object. In this paper, the successful application of EM sensors for on-line monitoring of phase transformations and to detect decarburisation in steels in a laboratory environment has been demonstrated. Industrial field trials further confirm the sensor's capability to monitor phase transformations and molten steel flow in a SEN during continuous casting.

Acknowledgements

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