Real-time in-line steel microstructure control through magnetic properties using an EM sensor

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Abstract

Magnetic and electric properties (such as low field relative permeability and resistivity) are sensitive to changes in both steel microstructure and temperature. Recently an electromagnetic (EM) sensor system (EMspec™) has been installed to non-destructively on-line monitor the phase (microstructure) transformation in strip steels during the cooling process after hot rolling. To use an EM system to provide dynamic control via varying the cooling strategies or heat treatment using sensor feedback, which can give higher quality steel products with excellent mechanical properties at reduced cost, requires accurate interpretation of the EM sensor signals and predictive capability of the signals from desired microstructures at the relevant temperatures. A 3D FE model is reported here that allows the EMspec™ sensor output (Zero Crossing Frequency, ZCF) to be related to the steel microstructure (phase fraction) using the relationships between permeability and resistivity with microstructure and temperature. The model has been verified by room temperature measurements on various steel grades samples (varying microstructure and strip thickness). High temperature experimental tests have been carried out using a lab-based furnace and run-out table (ROT) with cooling system, mimicking the real-time monitoring of phase transformation of steel strip products. The experimental results have been compared to predicted sensor signals for the known transformation behaviour, determined independently using dilatometry. In this paper the process by which the model can be used to predict the ZCF values for different transformation behaviour, for example different ferrite fractions prior to bainite / martensite formation in a two phase steel, which in turn can be used to control the cooling strategy to achieve a desired microstructure and mechanical properties is discussed.

Keywords: low field relative permeability, electromagnetic sensor, microstructure, non-destructive testing, in-line measurement

1. Introduction

Real-time microstructure monitoring during hot processing of steel using electromagnetic (EM) sensors, and dynamic control via cooling strategies or heat treatment using EM feedback, can give higher quality steel products with reduced cost. Reheated steel slab passes through the rough rolling and multiple finish rolling mills in order to achieve the desired product geometry, subsequently the steel strip goes through the cooling process, where the steel microstructure transforms from austenite to ferrite, pearlite, bainite and/or martensite, on the run-out table (ROT) before final coiling [1, 2]. Careful control over the phase transformation through the cooling trajectory is crucial to develop the desired steel microstructure that determines the mechanical properties required by customers. Currently control is indirect relying on temperature measurement and mill models for the transformation behaviour of a given steel grade. These models are typically fitted to account for mill specific variables and can require additional fitting when new steel grades or processing windows, outside the current database, are introduced. It is highly desirable to have a more direct measure of steel microstructure, which can be achieved using EM sensors. Recently an EM sensor system (EMspec^{TM} system) has been installed in the ROT of a hot strip steel mill for in-line monitoring of microstructure transformation on cooling [2]. The materials magnetic and electrical properties, low magnetic field relative permeability and resistivity respectively, are directly related to the steel microstructure and changes in these can be detected by the EMspec^{TM} system to characterise the phase transformation during steel strip cooling [2-5].

To achieve accurate EM signal interpretation requires knowledge of the temperature-electromagnetic properties (permeability and resistivity)-microstructure relationships. Finite element (FE) based micro models considering phases and phase distributions have been developed for predicting low field permeability from different steel microstructures, as shown in figure 1a. Research on the relationship between low field permeability and phase fraction in steel with ferrite-austenite or ferrite-pearlite microstructures at room and elevated temperatures has been reported [6, 7] based on experimental measurement and use of the microstructure model. 3D FE models of laboratory cylindrical and U-shaped EM sensors, such as shown in figure 1b [6], have also been developed that can accurately represent the experimentally measured real inductance and can be used to determine the low field permeability of steel samples, which can be related to properties, such as tensile strength in DP steels [9]. The EMspec^{TM} sensor system has been developed to monitor steel microstructure at elevated temperatures (below the Curie temperature of approx. 760°C) in the production environment taking advantage of the system being non-contact, inexpensive, having a fast response and being unaffected by water and the surrounding high temperature environment. To fully exploit this system there is a need to be able to quantitatively relate the signal to the microstructure taking into account the high temperature characteristics of the material and industrial sensor design, which has not been previously reported.

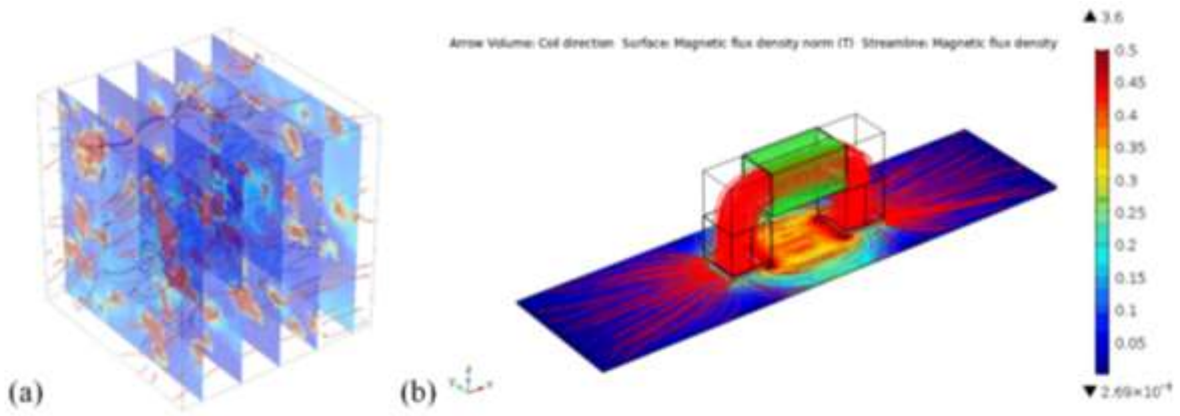

Fig.1 (a) FE modelled results of magnetic flux distribution for a 30% ferrite (70% austenite) microstructure where the red (and yellow) colour indicates a higher flux density, which occurs in the ferrite regions [7]; (b) FE model for a laboratory U-shaped sensor on a strip steel sample showing the surface contour plot of the magnetic flux density in the U core and sample; red streamlines indicate the magnetic flux density in ferrite core and sample surface and green streamlines indicate the current direction in exciting coil [6].

In this paper a robust full quantitative and predictive approach to relate the EM signals from the EMspec^{TM} system to microstructure (transformed fraction), with validation is introduced. A 3D FE macro model developed using COMSOL Multiphysics, for the commercial EMspec^{TM} sensor is described, along with its verification using measurements for different steel microstructures at room temperature. Using this model the sensor output of zero crossing frequency (ZCF) can be predicted, using inputs of low field permeability values, determined from the microstructure model [8] and resistivity values that are either measured or reported in the literature [9]. High temperature dynamic cooling tests using a laboratory bespoke furnace and ROT system have been carried out and the model prediction (for known transformation behaviour determined independently using dilatometry) compared with the measurement. This approach, mimicking the real-time monitoring of phase transformation of steel products, as described in figure 2 and reported in [2] allows the principle for control of cooling strategies during the production process to achieve a desired microstructure and mechanical properties to be proposed.

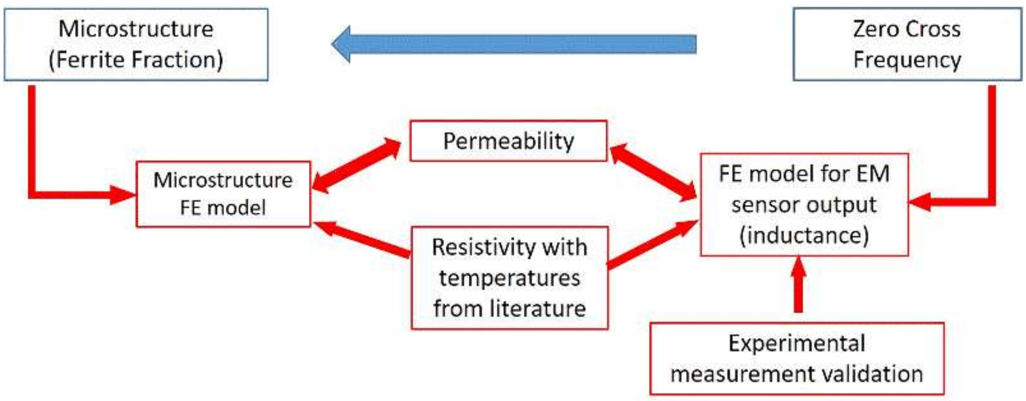

Fig.2. Flow chart showing the logic of interpretation of microstructure to sensor signals.

2. The EMspec™ system

The EMspec™ sensor consists of an H shaped non-conducting ferrite core, with 1 exciting coil and 2 sensing coils (1 active, 1 dummy), as shown in figure 3. The sensor head is normally set in a ferritic stainless steel canister, which is used to protect the sensor head from the environment (high temperature and humidity), from damage during use in the hot strip mill and also to shield the sensor from signals produced by other metallic components or operating equipment. This is placed in a housing which provides a water jacket to keep the sensor head at room temperature while measuring a hot steel sample. The sensor is installed between the rollers of the steel strip mill run out table and is able to monitor the steel phase transformation during the cooling process [2].

The active sensing coil detects the voltage induced in the steel by the exciting coil while the dummy coil combined with the sensing coil zeros the signal when there is no sample present (the dummy coil effectively measures the canister protecting the sensor). The EMspec™ exciting coil runs simultaneously at 8 frequencies ranging from 0.375 – 48 kHz and the magnetic field experienced by the target steel is low which corresponds to the Rayleigh region [2, 10]. The inductance versus frequency spectrum, which is affected by both the target steel sample permeability and resistivity, is calculated by a digital signal processor (DSP) based on a fast Fourier transform of the excitation current and the induced voltage [2]. The zero-crossing frequency (ZCF), defined as the frequency at which the real inductance equals zero, or when the phase angle of the inductance spectra equals -90°, deduced from the inductance phase spectra is the output signal used for this system, as it has relatively low sensitivity to any changes in lift off (from the set point of 40 mm) between the steel and sensor on the ROT [11]. Details of the phase angle of the inductance spectra response to different targets are described in [12].

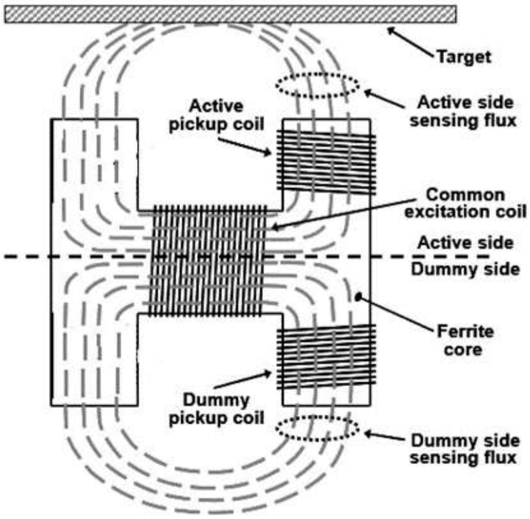

Fig. 3. Schematic diagram of an H shaped sensor such as that used in the EMspec™ system [2, 10].

3. Modelling of the EM sensor

A 3D FE model of the EMspec™ sensor installed on the lab-based ROT has been developed using the AC/DC module in Comsol Multiphysics with the aim of getting a quantitative transformation fraction from the EMspec™ measurements. The model with frequency domain allows a study of the relationship between sensor signals and permeability/resistivity of the steel sample.

3.1 Governing equations

The model is based on solving Maxwell's equations using certain boundary conditions, which can be written as [13]

$$(j\omega\sigma - \omega^2\varepsilon_0\varepsilon_r)A + \nabla \times H = J_e$$

$$(\mu_0^{-1}\mu_r^{-1}B) = H$$

$$\nabla \times A = B$$

Where A is the magnetic vector potential, H is magnetic field, J_e is external current density, ω is angular frequency, B is magnetic flux density, ε_0, ε_r are vacuum and relative permittivity respectively and μ_0, μ_r are vacuum and relative permeability respectively.

The boundary conditions used in the model describing relationships between two media in an AC power electromagnetic problem can be expressed as

$$n \times A = 0$$

Where n is the normal vector and A is the magnetic vector potential. The magnetic insulation boundary is applied to the symmetry planes of the model domain as it sets the tangential component of the magnetic potential A to zero. The inductance derived from the model can be expressed as

$$L_r = real(mf.VCoil_e/(mf.ICoil_s \times mf.\omega \times 1j))$$

$$L_i = imag(mf.VCoil_e/(mf.ICoil_s \times mf.\omega \times 1j))$$

Where L_r and L_i are the real and imaginary part of the inductance respectively, $VCoil_e$ is the excitation voltage and $ICoil_s$ is the induced current of the sensing coil, and ω is angular frequency.

3.2 Model description

The sensor head and the canister geometries were built based on the dimensions of the EMspec™ system provided by Primetals Technology Limited, as shown in figure 4a. The sensor was set to be above a 500×500 mm^2 steel plate, which could have varying thickness. A sphere (radius 5 times the sensor length) is added to encircle the sensor and canister geometries. The added sphere is filled with air in order to simulate the sensor working environment (the air sphere is not shown in figure 4a). The sensor operates at a 40 mm lift off from the sample and the model runs simultaneously at 8 frequencies from 0.375 – 48 kHz. The materials properties used in the model are listed in table 1. The permeability values have been determined for the low magnetic field appropriate for the EMspec™ sensor for different steel microstructures using a FE microstructure model and experimental measurements [7, 14]. The conductivity of air is set at a low value to help the convergence of the model. The coil geometry analysis feature is used in the study step and a parametric sweep is used to define different permeability and resistivity values of steel samples during the model fitting stage.

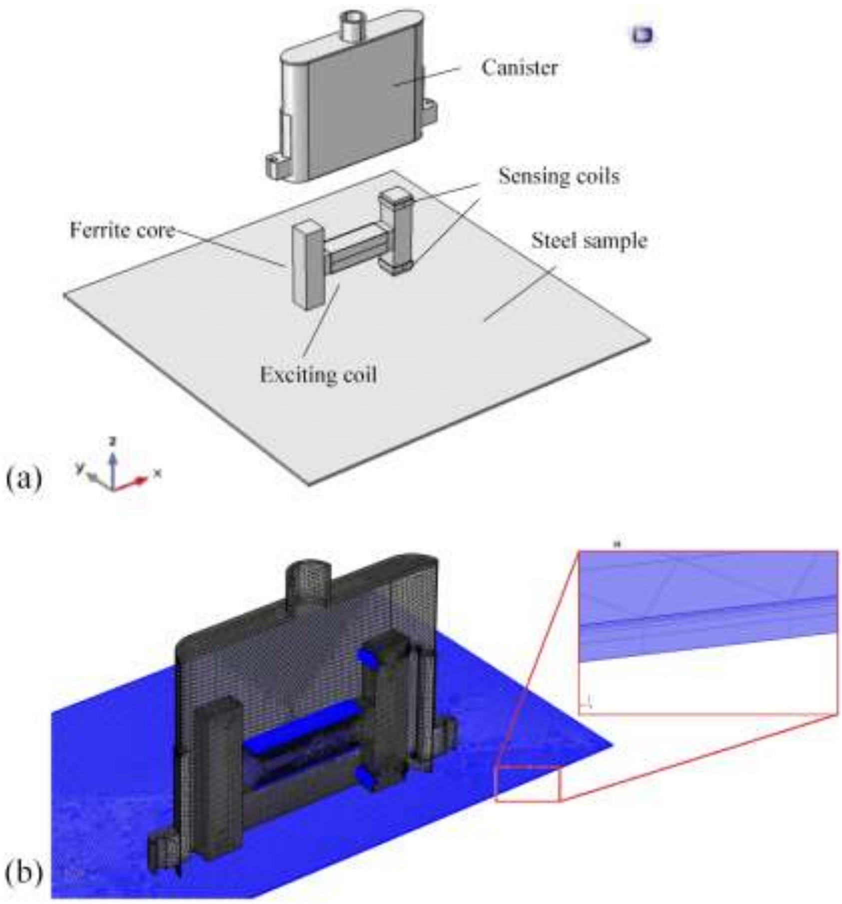

Fig. 4. Geometries of the EM sensor (a) and symmetric meshed model (b) for the EMspec^{TM} system (the canister is lifted above the sensor to show the sensor head geometry).

Table 1 Magnetic and electrical properties used in the model.

Materials	Ferrite core	Copper wire	Canister	Air
Conductivity, S/m	1	6×10^{7}	4.2×10^{6}	50
Relative permeability	2300	1	90	1

3.3 Refine meshing

The full 3D FE model was established to predict the ZCF for a range of steel grades at room and high temperatures, which meant the magnetic permeability can vary from hundreds to thousands, e.g. 90% ferrite-austenite microstructure has a permeability of about 100 at room temperature but it can go up to 2000 at 700°C [8]. It was found that the initial full 3D FE model used had insufficient mesh elements (limited by local computer workstation capability to solve the model: CPU: Intel Xeon E5-1620 3.70GHz; RAM: 64.0 GB) to accurately predict the ZCF for high permeability samples (e.g. electrical steels at room temperature or structural strip steel samples at high temperature) when the minimum mesh element was larger than the skin depth. Therefore a symmetrical model was developed to reduce the geometry domain such that a finer mesh scheme can be applied to allow the skin depth to be solved while keeping the model hardware requirement reasonable (i.e. suitable for the workstation available). The magnetic insulation boundary was applied to the symmetrical planes of the model. Figure 4b shows the symmetrical model with meshing. To refine the mesh in the key areas, the Boundary Layer and Swept Mesh method (refining the domain in the thickness direction) were applied to the coil and sample domains. The minimum layer thickness is 0.02 mm, which guarantees there are sufficient mesh elements within the skin depth (skin depth for an electrical steel sample being tested at 6000 Hz is about 0.08 mm, determined using the equation for skin depth of $\delta_s = \sqrt{1/\pi f \mu \sigma}$ where f is the frequency, μ is the relative permeability and σ is the conductivity). The total number of elements for the model is of the order of 1.3×10^6.

4 Hight temperature test with ROT and furnace system

EM sensor systems have been used online on the run-out table of hot strip mills to monitor steel through transformation [15] and provide feedback for processing control to improve the final product [16], where in each case the signal has been correlated to the state of transformation using known transformation behaviour (from mill models [15] or dilatometry [16]). The EM sensor studied in the present work is the same as used in [15] and is installed in a laboratory bespoke ROT and furnace system, as shown in figure 5. The system enables continuous EM measurements to be made for reheated steel strip as it cools through transformation at different cooling rates e.g. natural air, forced air and water jet cooling.

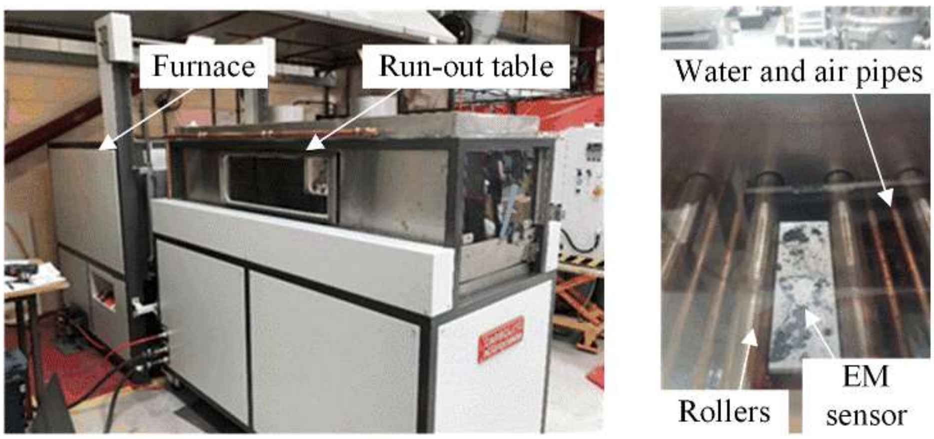

Fig. 5. Images of furnace and ROT system and the sensor in its protective housing installed between the rollers on the ROT.

To illustrate the capability of the sensor system to continuously monitor transformation and to relate the signals to predicted behaviour using the developed sensor FE model, experiments were carried out using a steel grade that was selected as it transforms to a mixed ferrite and bainite microstructure below the Curie temperature under the cooling rates achievable with the furnace-ROT system. A 500×500×3 mm thick 2.25 Cr-Mo (composition in table 2) steel sample was loaded into the hot furnace and heated to 980 °C. The temperature of the sample was monitored by a K-type thermocouple which was located 1.5 mm through thickness and approximately 150 mm from the edge of the sample that would be closest to the back of the furnace. The sample was held in the furnace for approximately 5 minutes and the temperature measured (to ensure the sample reached the desired temperature – a short reheating time was used to minimise any surface oxidation / decarburisation) before being rolled out of the furnace over the sensor where the sensor measurement commenced with the ZCF being recorded (at 20 measurements per second) while the sample cooled. The sample was moved back and forth over the sensor to ensure uniform cooling (avoiding local variations due to the presence of the rollers).

Table 2. Chemical composition of Cr-Mo steel (wt %)

C	Si	Mn	P	S	N	Al	Cu	Cr	Ni	Nb	Mo	V	Ti
0.11	0.29	0.58	0.013	0.002	0.010	0.033	0.09	2.12	0.06	0.004	0.94	0.01	0.003

Dilatometry was performed on a 10×4×3 mm sample to determine the transformed fraction with temperature. The sample was heated to 950 °C and held for 5 minutes and then cooled using Newtonian cooling with a cooling rate between 800 °C and 500 °C of 4.25 °C/s, which is the rate measured for the plate during natural air cooling on the ROT. The phase fraction transformed was calculated by using the Lever rule on the dilation data.

5. Results and discussion

5.1 Magnetic field

Figure 6a shows the magnetic flux flow inside the ferrite core and associated distribution in the canister and at the surface of a steel sample. The flux flows from one side of the H ferrite core and returns back to the other side, during which the canister and the steel sample are magnetized, as shown in figure 6b where the current direction inside the exciting coil generates a magnetic flux flowing through the H core and the sensing coils. The flux flows upwards and downwards to magnetize the canister and the steel sample respectively, which in turn generates opposite current flows in the dummy and active sensing coils. The output of the sensor is a subtraction between the active sensing and dummy sensing coils.

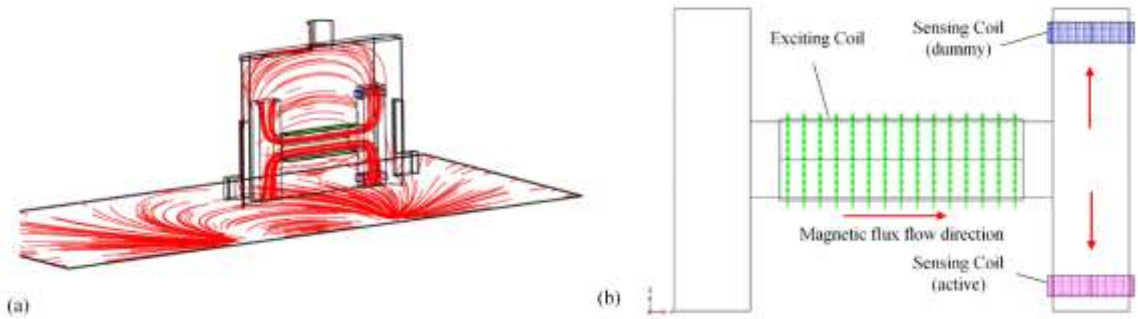

Fig. 6. (a) Magnetic flux flow inside the ferrite core, canister and at the surface of a steel sample; (b) Coil current directions and induced magnetic flux flow direction inside the ferrite core.

Figure 7 shows the contour plot of the magnetic flux distribution in the model, which follows the flux flow pattern shown in figure 6a. The magnetic flux flows from one sensor foot to the other through the sample causing the magnetic flux density in the area between the two sensor feet to be higher than in other areas at the sample surface. It can be seen that the canister is also magnetised by the exciting coil and thus will influence the signal detected by the active sensing coil. The magnitude of magnetic flux in the canister is larger than that in the steel sample because the canister is closer to the exciting coil and there is a 40 mm lift-off between the sensor feet and the steel sample.

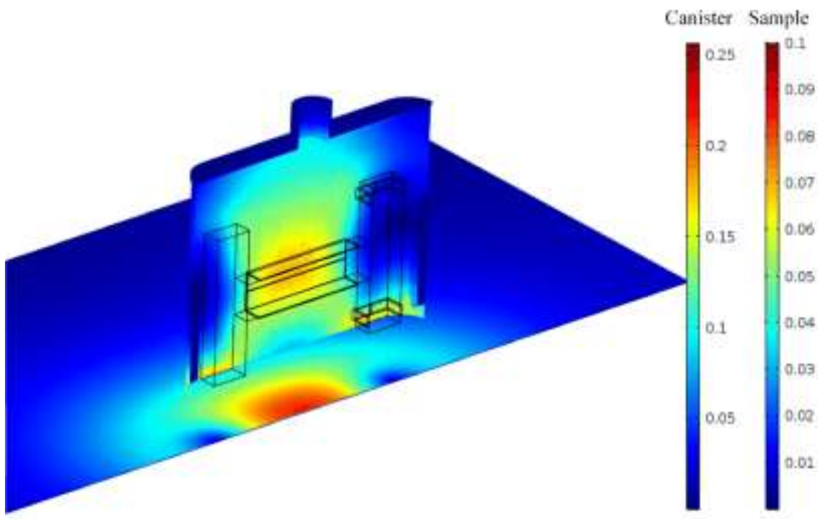

Fig. 7. Contour plot of magnetic field distribution in the model, note the different colour scales for the magnetic flux in the sample and in the sensor canister.

5.2 Model validation

The model was first validated by room temperature measurements for different steel samples, selected to have a range of resistivity and low field relative permeability values. The sample dimensions, low field relative permeability and resistivity values were used as input into the model to determine the predicted sensor signals. Figure 8 shows the modelled inductance against frequency curves for four steel samples (duplex stainless steel, low carbon low alloy fully martensitic steel, a low carbon ferritic steel and a ferrite pearlite steel) with different thicknesses (1, 2, 3.7 and 1.9 mm respectively). At low frequency, the steel sample is magnetised by the sensors magnetic flux and the inductance is positive (the magnitude of which is affected by the sample low field relative permeability and thickness). When frequency increases, eddy currents are generated in the sample. The eddy currents induce a magnetic field, which is opposite to the primary one generated by the sensor, therefore the inductance decreases and the sample resistivity has a strong influence on the sensor signal, the low field relative permeability and sample thickness also affect the signal. At high frequencies, the eddy currents decrease as the skin depth decreases with the frequency, so the inductance curve gradually levels at a certain value, which is influenced by the sensor design.

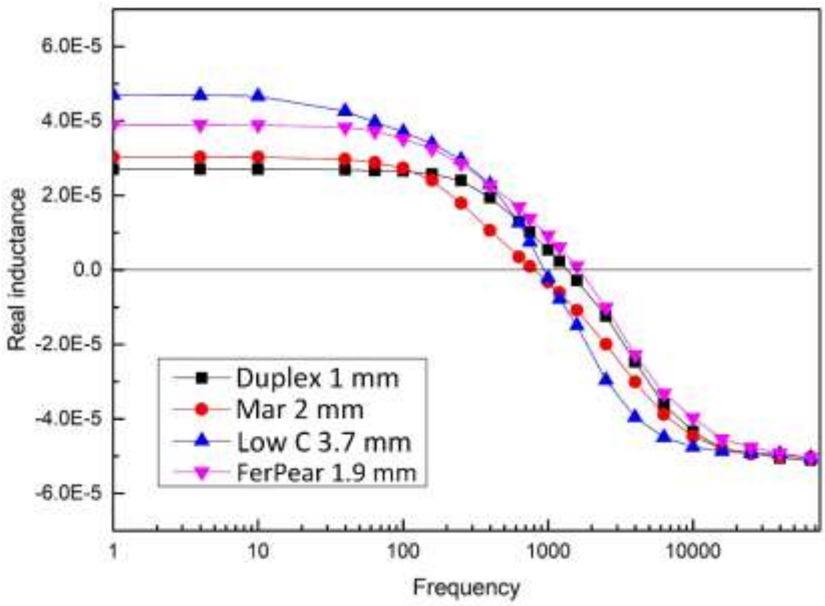

Fig. 8. Modelled inductance against frequency curves for four reference steels, each with different thicknesses, at room temperature.

The zero-crossing frequency, derived from the inductance curves, have been obtained and compared with the measurement results using the EMspec^{TM} sensor. Figure 9 shows the modelled ZCF values compared with measurements for a wide range of steel grades, including those described above, at room temperature. The dash lines indicate the 10 % difference between modelled and measured values. The model shows agreement with measurements within ±10 % error, with a small consistent over prediction in the ZCF compared to the measured value. This may due to the slightly different lift-off being used in the modelling work compared to the furnace-ROT measurements; a 40 mm lift off was used in the model, which fits with the value designed for the experimental system and matches the industrial set up [15].

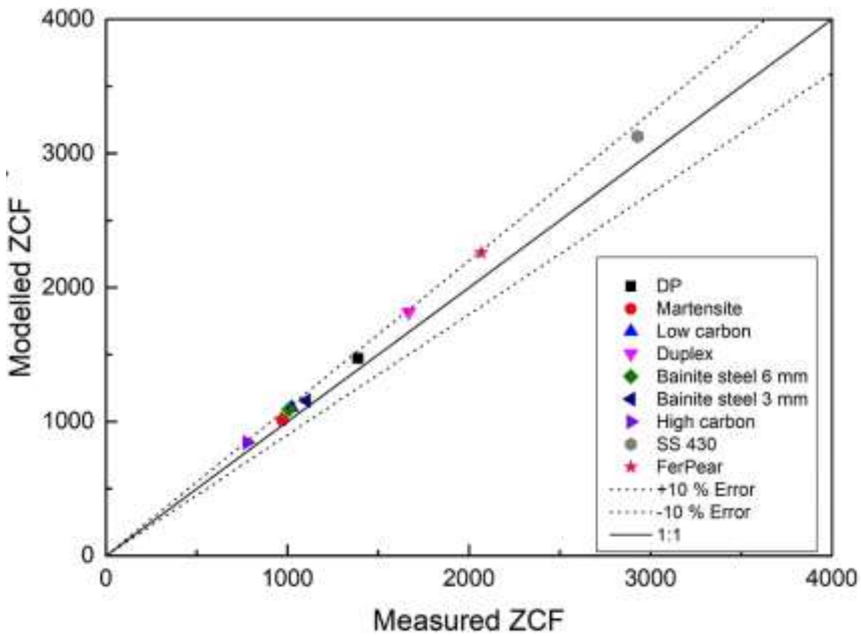

Fig. 9. Modelled and measured ZCF values with ±10 % error.

5.3 ZCF prediction for high temperatures tests

To predict the EMspec^{TM} sensor signal for steels undergoing transformation at high temperature then the low field relative permeability values of single phase and partially transformed microstructures (ferrite + austenite with 0-100 % ferrite fraction) are required. Low field relative permeability values for ferrite-austenite microstructures at high temperature from 500-721°C have been predicted using a validated FE permeability-microstructure model [8]. Low field relative permeability values from the model are shown in figure 10a and it can be seen that the low field relative permeability values increase with increasing temperature (below the Curie temperature) as well as with increasing ferrite fraction, as ferrite is ferromagnetic (austenite is paramagnetic and has a relative permeability value of 1) and the free energy to allow domain wall movement increases with temperature. Resistivity values for a low carbon ferritic steel have been obtained from the literature [9]. The values for austenite (i.e. the resistivity above the ferrite to austensite transformation temperature) have been extrapolated to lower temperatures (i.e. polynomial line of best fit is used to determine the resistivity at different temperatures for the microstructures). The values for different ferrite fractions (i.e. microstructures during transformation) have been obtained by using a power law relationship between the values for fully ferrite and fully austenite microstructures: equation $\rho_{eff}^{\beta} = (1-f)\rho_1^{\beta} + f\rho_2^{\beta}$ (β=1/3) where ρ_1 and ρ_2 are the resistivity values for the first and second phase respectively, f is the fraction of the second phase and β is a dimensionless parameter. The power law equation is widely used when considering the property of a material that has two or more components [14, 17, 18] and the value β=1/3 has been reported to give good agreement with measurement at ferrite fraction above 40 % (sample with ferrite fraction below 40 % would require a much smaller value to give good fitting [17]. The appropriate low field relative permeability and resistivity values for the microstructure state during transformation have been used as inputs into the FE sensor model to determine inductance against frequency curves, from which ZCF values can be derived accordingly. The sample size used in the model is 500×500×3 mm^3 with sensor lift-off of 40 mm, which matches with the experimental set up used.

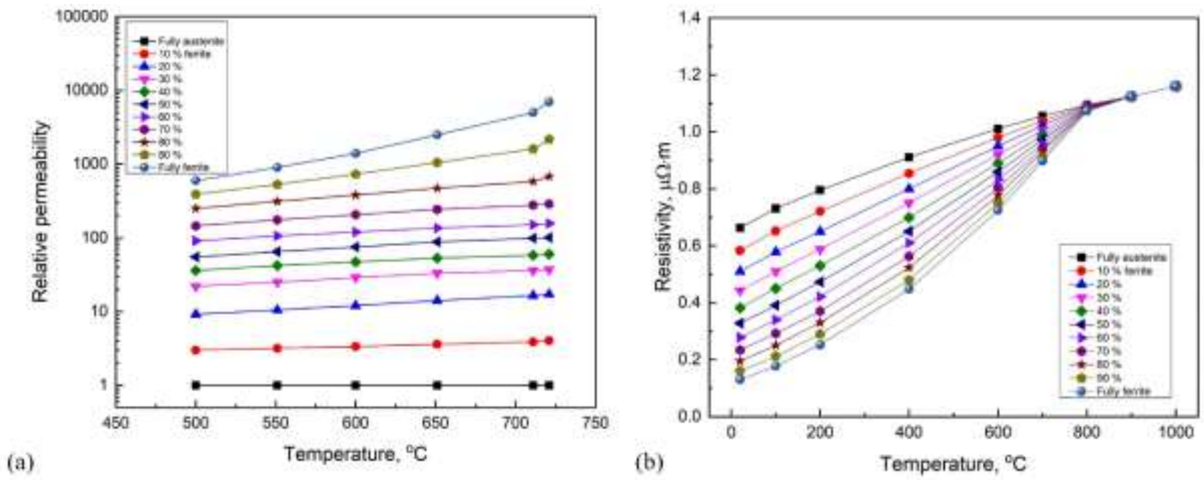

Fig. 10. (a) Permeability values with temperature obtained from the FE microstructure model [6] and (b) resistivity values with temperature for mixed ferrite + austenite microstructures over the range of 0-100 % ferrite fraction.

Figure 11 shows the modelled ZCF changes output from the FE sensor model for mixed ferrite-austenite microstructures over the range of 0-100 % ferrite fraction plotted as a percentage change with respect to the value of maximum difference, i.e. (X-min_{zcf})/(Max_{zcf} - min_{zcf}) % where min_{zcf} is for austenite at room temperature and max_{zcf} is for ferrite at 721°C. The ZCF values increase as the temperature increases because larger low field relative permeability and resistivity values are seen at higher temperatures. The results can now be used to predict the EMspec^{TM} sensor signal for high temperature tests for transformation during cooling on the furnace-ROT or, in reverse, the approach can be verified using the experimental method. It should be noted that the FE sensor model will allow the influence of sample geometry (thickness and size for example if microstructure variations close to sample edges are desired), operation (lift off between sample and sensor, temperature) and steel (microstructure) to be assessed and the signals to be related to microstructure.

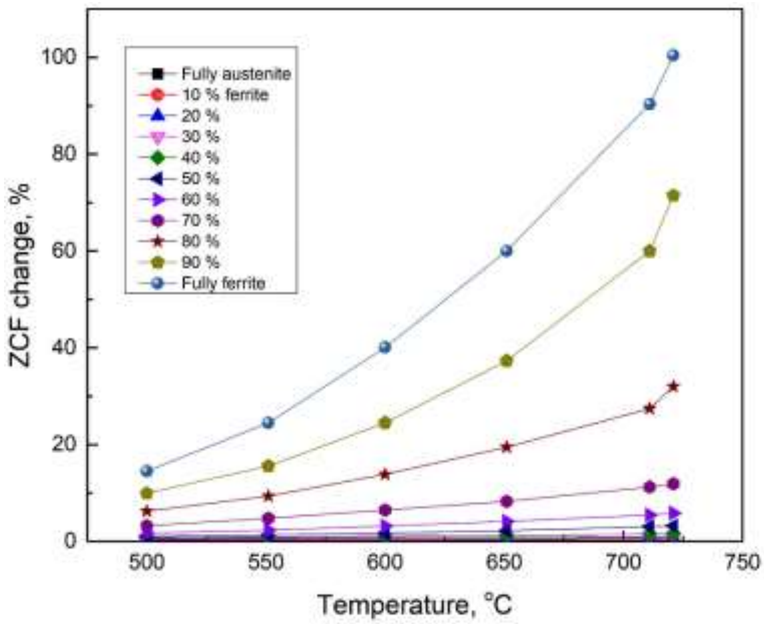

Fig. 11. Predicted ZCF values for ferrite-austenite microstructures (0-100 % ferrite) against temperature.

5.4 High temperature tests

A Cr-Mo steel was used to validate the EMspec^{TM} sensor model for high temperature tests. A dilatometry analysis was used to determine the transformation behaviour against temperature for the same cooling rate as obtained using natural air cooling on the furnace-ROT system. The low field relative permeability of bainite at elevated temperatures is required to predict the full transformation microstructure response as the Cr-Mo steel transforms from austenite to bainite microstructure at the cooling rate used. The low field relative permeability of bainite was estimated using the relationship between low field relative permeability and temperature for pearlitic steel from the FE micro model and experimental results [8]: a parallel trend to that observed for the fully pearlite microstructure low field relative permeability with temperature curve was assumed for the bainitic steel using the measured room temperature low field relative permeability values of 59 for the 0.8 wt% C pearlitic steel and 88 for the 2.25 Cr-Mo bainitic steel. This assumption was made on the basis that both these microstructures have a large number of domain pinning sites - finely spaced carbides / lath boundaries for bainite compared with ferrite/cementite lamellae boundaries in pearlite and parallel trends with respect to temperature can also be observed for 0.17, 0.38 and 0.80 wt% carbon steels (ferrite-pearlite microstructures with different pearlite fractions) up to 600 °C [8]. The resistivity with temperature during transformation was predicted using the power law for the extrapolated bainitic and austenitic trends taken from the literature as described earlier [9].

The sample was loaded into the furnace and EM sensor measurements were carried out when the sample was cooled on the run-out table. The dilatometry analysis was carried out on the steel to determine transformation fraction with temperatures, which is shown in figure 12 (red curve). The Cr-Mo steel starts to transform at about 525 °C with transformation being complete about 385°C. The measured ZCF from the EMspec^{TM} sensor is also illustrated in figure 12 (blue solid curve). Above approximately 480 °C, the ZCF has a consistent low value, which would be expected from a sample that is fully austenitic and therefore paramagnetic. At approximately 480 °C, the ZCF begins to increase signalling the presence of ferromagnetic (bainite) phase in the steel. This is a lower temperature than expected based on the dilatometry results for transformed fraction (red curve), which may be due to slight differences in cooling rate and/or temperature measurement for the small dilatometer sample and large steel plate on the ROT. In between 390-480 °C there is a competing effect of increase in permeability due to the bainite transformation (i.e. increase in the amount of ferromagnetic phase present); and decrease in low field relative permeability and resistivity of bainite as temperature decreases. The subsequent increase in ZCF suggests that the increase in low field relative permeability due to bainitic transformation is more significant. At a temperature of about 390 °C the sample is either fully transformed or very close to being fully transformed. Therefore the decrease in low field relative permeability and resistivity with decreasing temperature becomes more significant, which results in the decrease in ZCF. The final microstructure on the cooled plate is fully bainitic.

The predicted ZCF from the FE model is also shown in figure 12 (blue hollow symbol curve). The modelled ZCF follows the same trend as the measured ZCF and values agree very well with each other. The small difference in the peak ZCF values may be due to errors in estimated low field relative permeability and resistivity values. The results show that the EMspec^{TM} signal can map the full transformation of steel below the Curie temperature and that the FE sensor model can determine the sensor ZCF values for a desired microstructural transformation with temperature.

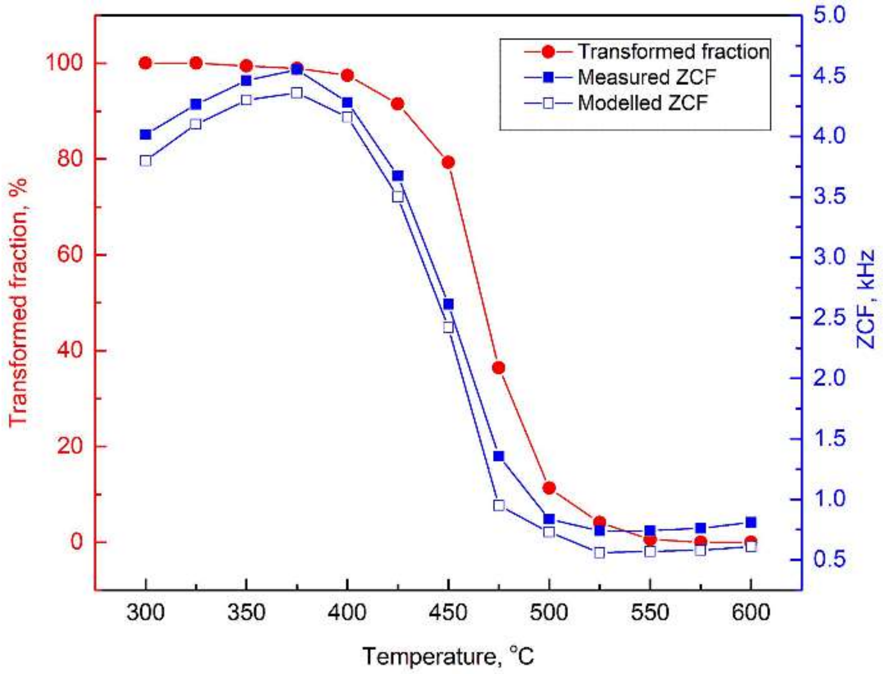

Fig. 12. Phase transformed fraction, measured and modelled ZCF with temperature.

With the established models for ZCF - low field relative permeability/resistivity – microstructure - temperature, the EMspec^{TM} ZCF with respect to microstructural state can be predicted. Using continuous cooling transformation (CCT) diagrams or dilatometry to obtained the desired transformation with cooling rate (or time) for a given steel the EMspec^{TM} signal can be determined and during steel production dynamic feedback could be used to control cooling to ensure the desired microstructures (and hence mechanical properties) can be achieved.

The relationships of temperature-permeability/resistivity-sensor signal (ZCF) can also be used to obtained permeability at any (known) temperature and estimated resistivity (for the known temperature) from the sensor signal, which can then be used to give information on the expected microstructure (phase fraction), mimicking the real-time monitoring of phase transformation of steel products. In a reverse engineering, if the phase transformation fraction is known (based on the desired product) then it can be translated into an expected permeability and resistivity values from which the ZCF value can be obtained through the model, which can help to control the cooling rate at the hot roll mill to achieve a desired microstructure.

6. Conclusions

A 3D FE model of the EMspec^{TM} electromagnetic sensor has been developed taking into account the sensor, canister housing and sample geometry. The model has been verified against sensor measurements using the EMspec^{TM} system for steel samples with different microstructures and thicknesses at room temperature. The model is for any austenite-ferromagnetic mixed structures, as an example, the sensor response and measured ZCF value have been predicted for austenite-ferrite microstructures over a range of temperatures representative of various transformation states. A high temperature test using a Cr-Mo steel, selected to transform from austenite to bainite (ferromagnetic) below the Curie temperature was carried out on a lab based ROT and furnace system and the predicted ZCF agrees well with the measurement, indicating the accuracy of the model. The main conclusions are as follows:

1. The EMspec^{TM} sensor model was used to predict ZCF values for different steel grade samples with different thicknesses at room temperature. The modelled values were within a 10 % difference when compared with experimental measurements.

2. The ZCF values have been predicted for austenite-ferrite (0-100 % ferrite fraction) microstructures at high temperatures. The relationships of temperature-low field relative permeability/resistivity-sensor signal (ZCF) can be used to obtained permeability at any (known) temperature and estimated resistivity (from the known temperature) from the sensor signal, which can then be used to determine the microstructure (phase fraction), mimicking the real-time monitoring of phase transformation of steel products. Alternatively the ZCF for a desired microstructure transformation on cooling can be predicted and the mill cooling controlled to give the aim ZCF with temperature (or time) trajectory.

3. The model predicted ZCF values for the Cr-Mo steel when the sample is cooling on a lab based run-out table and furnace system, with known transformation kinetics obtained from dilatometry measurements. The modelled ZCF values follow the same trend as the measured ZCF values with an increase being seen due to transformation followed by a decrease after full transformation as the temperature decreased.

Acknowledgements

The authors would like to thank EPSRC for funding the RIME project under grant EP/P027210/1 and WMG, HVM Catapult and Primetals Technologies, Ltd for the provision of facilities and constructive suggestions.

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