COMSOL
CONFERENCE
2018 LAUSANNE

Use of COMSOL® AC/DC module to model an EM sensor deployed to monitor steel transformation during cooling from elevated temperatures

Jialong Shen[a], Will Jacobs[a], Lei Zhou[a], Peter Hunt[b] and Claire Davis[a]

a Advanced Steel Research Centre, WMG, University of Warwick, Coventry, CV4 7AL, UK

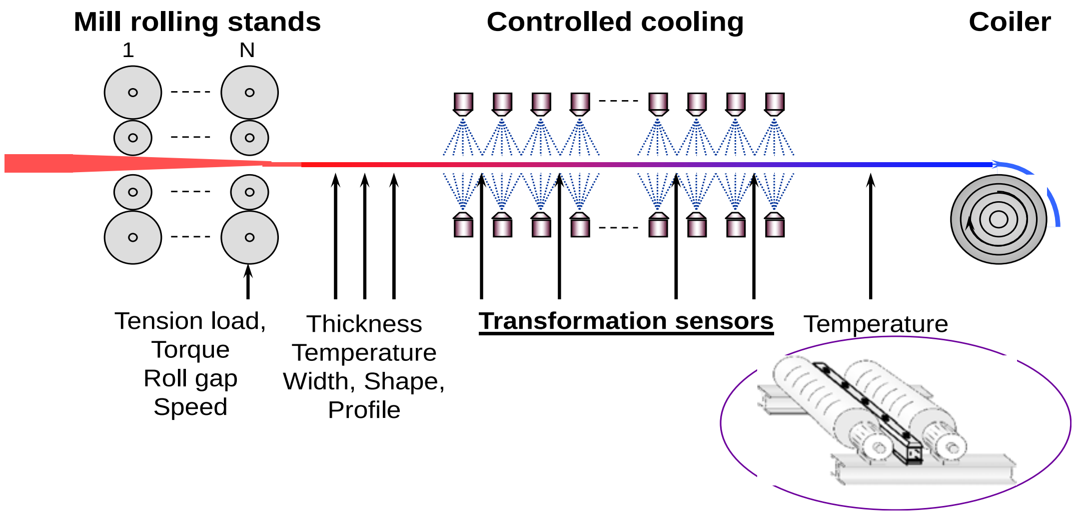
b Primetals Technologies Limited, 9 Aviation Way, Christchurch, BH23 6EW

23.10.2018

Industrial context and modelling problem

- Electromagnetic (EM) sensors are being used to measure microstructure and properties for steel during production in the manufacturing plants.
- (Semi-) empirical correlations between the sensor signals and material property of interest are the current approach.
- There is a need for models to be able to determine relationships rather than relying on empirical approaches and to be able to take into account additional factors such as sensor design, application geometry, new material grades / microstructures etc.
- Challenge to develop 3D models that can consider all the above effects.

Hot strip rolling process



Mill rolling stands

1 ---- N

Controlled cooling

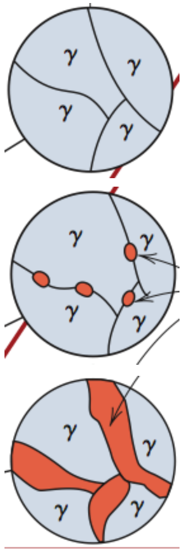
Coiler

Tension load,
Torque
Roll gap
Speed

Thickness
Temperature
Width, Shape,
Profile

<u>**Transformation sensors**</u>

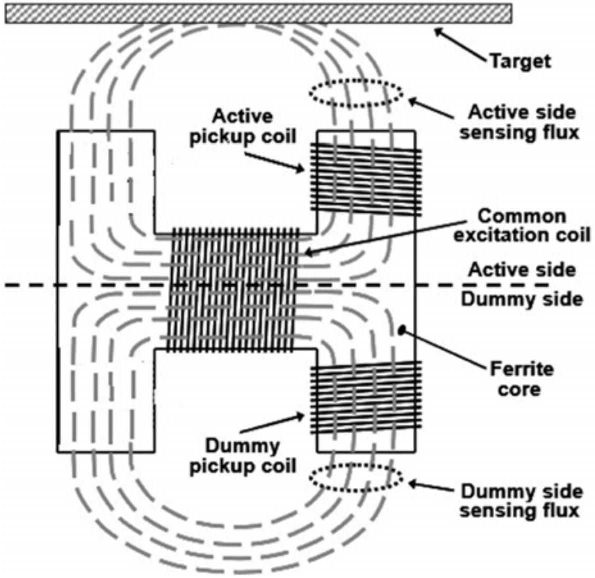
Temperature

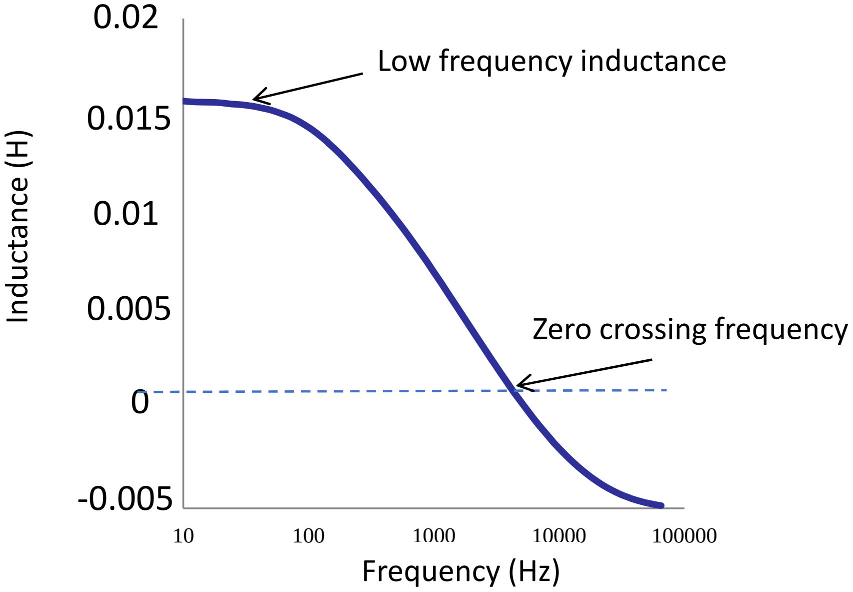


- Microstructures formed during the cooling process for hot-rolled strip steel production determines the mechanical properties required by customers
- Traditionally destructive testing (Metallography, SEM, EBSD, etc) is used for steel microstructure (quality) information
- Non-destructive real-time microstructure monitoring using EM sensors have been extensively used due to advantages of non-contact, inexpensive, fast response and being unaffected by water and high temperature environment

The EMspec^{TM} system

- The materials permeability and resistivity are related to the steel microstructure and hence changes in these can be used to characterise the mechanical properties (quality) during steel strip cooling
- The low magnetic field EM sensor is sensitive to variations of steel permeability and resistivity. The EMspec^{TM} system has been developed to monitor steel microstructure at elevated temperatures (below the Curie temperature of approx. 760°C) in the production environment
- The inductance versus frequency spectrum, which is affected by both the steel permeability and resistivity, is calculated; The zero-crossing frequency (ZCF) deduced from the inductance phase spectra is the signal used for this system,





EM sensor modelling using COMSOL® AC/DC module

- Aim: to establish the relationships between sensor signal (ZCF) and permeability/resistivity (microstructure) taking into account the high temperature characteristics of the material and industrial sensor design
- The sensor FE model was developed in the AC/DC module using the magnetic fields interface with a frequency domain study
- The model is based on solving Maxwell's equations using certain boundary conditions

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

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

$$\nabla \times A = B$$

- 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

$$n \times A = 0$$

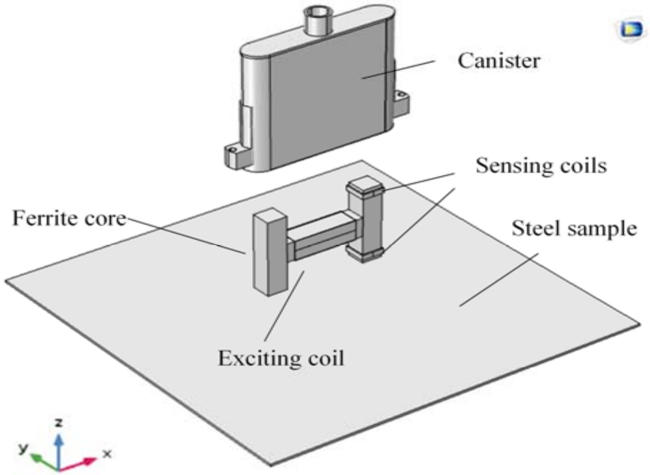
- The inductance derived from the model can be expressed as

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

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

EM sensor modelling using COMSOL® AC/DC module

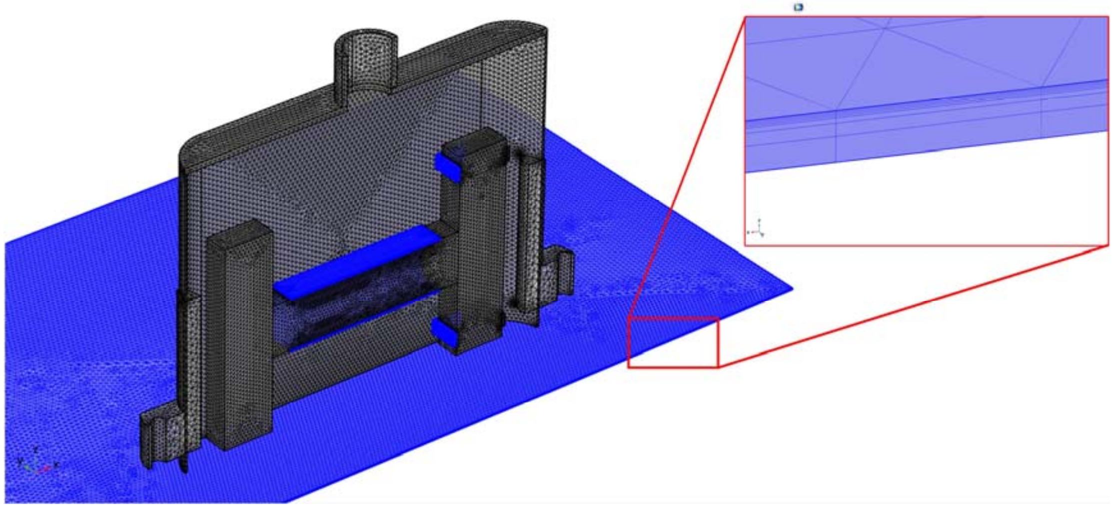
- The EMspec^{TM} sensor consists of an H shaped non-conducting ferrite core, with 1 exciting coil and 2 sensing coils (1 active, 1 dummy); a ferritic stainless canister is used to protect the sensor head from the environment and also to shield the sensor from signals produced by other metallic components or operating equipment
- The sensor was set to be above a 500×500 mm^2 steel plate with varying thickness; 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
- Numerical multiturn coil was applied to the exciting and sensing coil domains. An Auxiliary Sweep was used in the study to help model convergence at low frequency. 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.



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

EM sensor modelling using COMSOL® AC/DC module

- The full 3D FE model was established and worked well for steel grades, which all had relatively low values (< 300) of magnetic permeability, at room temperature
- The model had limited mesh elements (limited by local computer workstation capability to solve the model: CPU: Intel Xeon E5-1620 3.70GHz; RAM: 64.0 GB) which meant it was unable to accurately predict the ZCF for high permeability samples (e.g. electrical steels or samples at high temperature) when the minimum mesh element was larger than the skin depth.
- A symmetrical model was developed to reduce the geometry domain; 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.

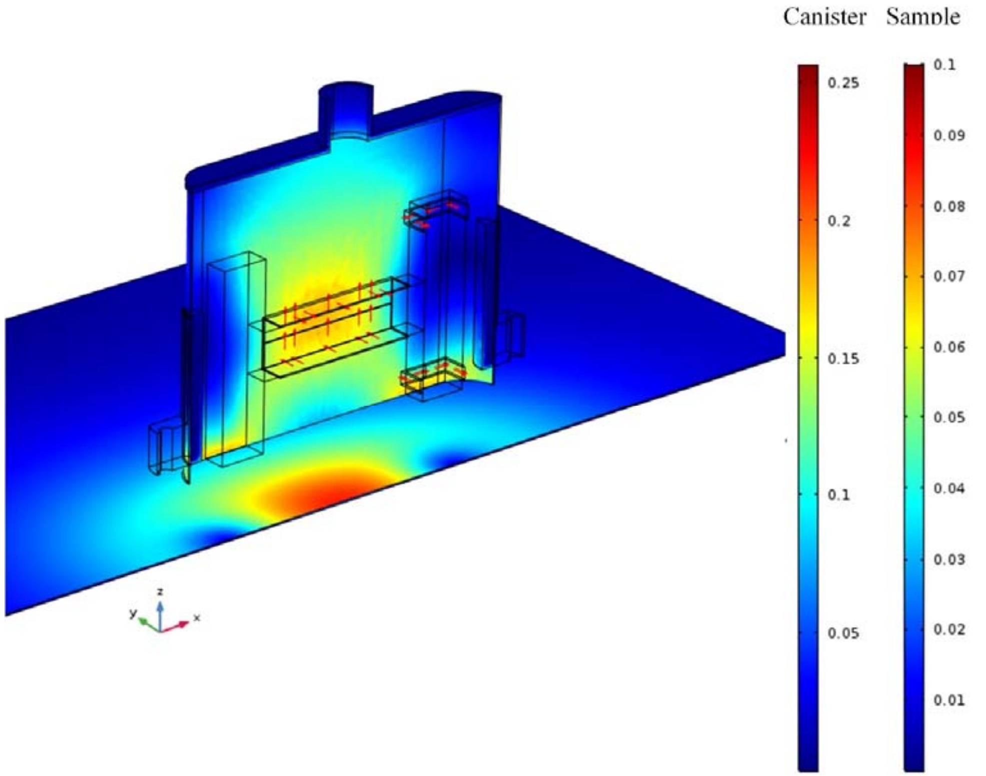


Magnetic field

- 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

- The canister is also magnetised by the exciting coil and thus will influence the signal detected by the sensing coil

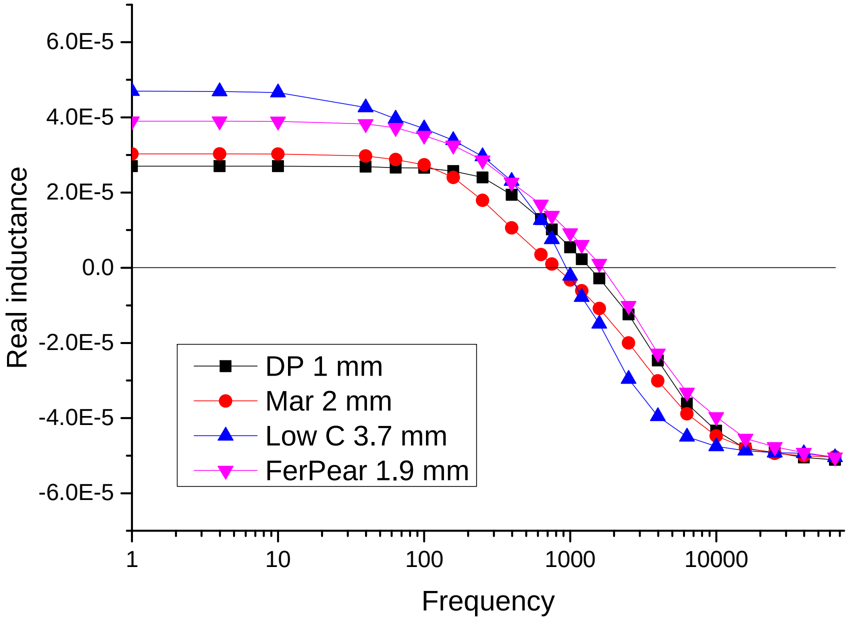
- The magnetic field in the samples was determined to be < 0.2 kA/m, which agrees well with the measured (using a Gauss Meter) value



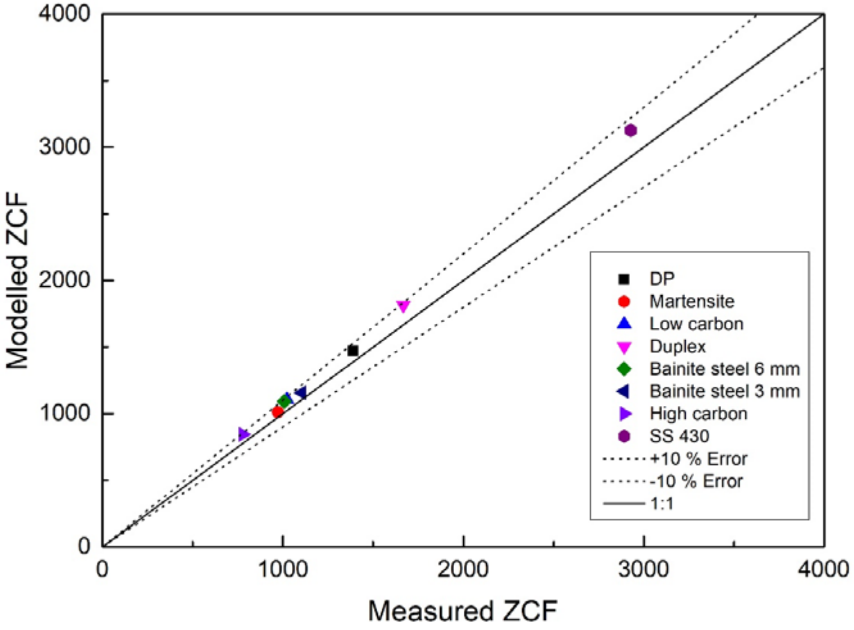
Magnetic field distribution in the sample and the canister; the red arrows indicate coil direction of exciting and sensing coils

Model validation

- Modelled ZCF derived from the inductance curve compared with measurements for a wide range of steel grades at room temperature. It shows excellent agreement is obtained for the sensor signal (within ±10 % error).



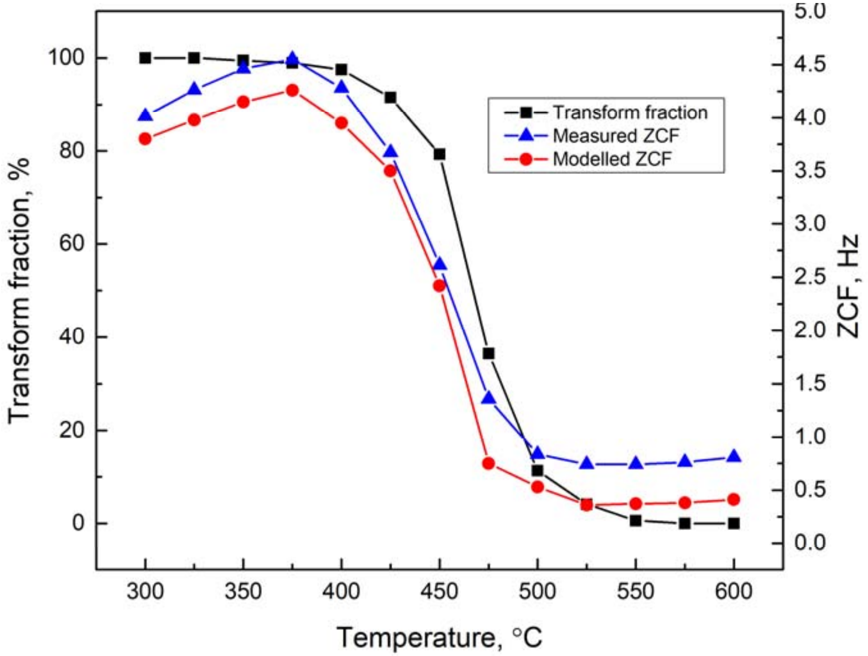
Modelled inductance for different steel samples at room temperature



Modelled and measured ZCF values with ±10 % error

High temperature ZCF prediction

- ZCF vs temperature curve during cooling for a Cr-Mo steel was predicted (for known transformation conditions) using the FE model
- The steel starts to transform at about 525 °C from austenite (paramagnetic) to bainite (ferromagnetic) with transformation being complete at about 385 °C. The measured ZCF increases as the transformation begins and reaches a peak when the steel is fully transformed. The ZCF then decreases due to the decrease of permeability and resistivity at low temperatures
- The difference between the modelled and measured ZCF when the transformation fraction < 40 % may be due to the ferromagnetic phase not being connected in the microstructure at these transformation fractions.



Modelled and experimental ZCF and transformed fraction with temperature for a Cr-Mo steel

Conclusions and future work

- The FE model has been verified against sensor measurements using the EMspec^{TM} system for steel samples with different microstructures at room and elevated temperatures.

- The model can be used to obtained the sample permeability at any (known) temperature (and hence resistivity) 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.

- Modelling for edge effects at high temperature to determine how close to the sample edge EMspec^{TM} sensors could be applied to give full coil width on-line inspection for uniformity.

- Modelling for the effect of run out table geometry (rollers) on the EMspec^{TM} signals and comparisons with the lab test signals.

- To provide a desired ZCF trajectory with temperature (or time) to achieve a specific microstructure for real-time control of microstructure development.

Thank you for your attendance!

Question ?