Modelling of the effect of microstructural variation on inductive sensor measurements of phase transformation in steel

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Abstract. The present paper is concerned with modelling the effect of decarburisation, oxidation, and the changing conductivity and permeability with carbon content and temperature in steel on the electromagnetic signal from an inductive sensor used to detect ferrite formation from austenite below the Curie temperature.

1. Introduction

After hot rolling, steel is cooled to obtain the microstructure and hence mechanical properties required by the customer. To increase microstructural homogeneity, and hence improved consistency in the mechanical properties, variations in temperature distribution and cooling rate must be avoided, therefore, accurate control of the cooling process is required.

Previous work on three different plain carbon steel compositions (0.03, 0.45 and 0.83 wt% C, designated respectively, low, medium and high carbon steel) showed that an electromagnetic (EM) sensor can successfully detect the formation of ferromagnetic phases below $T_c$ [1-5]. It was also revealed that the imaginary part of the trans-impedance value is non-linearly related to the ferrite volume fraction, over the range 0-30% ferrite, and depends on the morphology/distribution of the ferromagnetic phase so that it is influenced by the prior austenite grain size. Finite Element (FE) simulations using Maxwell 2D software package by Ansoft designed to enable prediction of the imaginary trans-impedance value from the microstructure showed that this method can be successfully used to model the experimental trends observed [1-3]. The combined results obtained through experiment and FE analysis have shown that the EM sensors can be used to directly monitor the ferrite formation in steel when this occurs below the $T_c$. In a previous paper, we discussed the experimental results that showed how for medium and high carbon steels, the EM sensor output is significantly affected by decarburisation and oxidation due to the presence of connected, or partially connected, surface ferrite pathways [4]. It was also shown that the operating frequency of the EM sensor affects the degree to which the decarburisation affects the sensor reading due to the increased eddy current effect and reduced sampling depth.
2. EM sensor design

The EM sensor design used to test steel rod samples, reported previously [1-4], has been shown to be capable of detecting the phase transformation in carbon steel during cooling below the \( T_c \). The sensor consisted of one primary (exciting) coil and one secondary (sensing) coil. The samples used during the experiments were 80 mm long and 10 mm in diameter.

Although the present paper is concerned with the experimental work and modelling carried out on rod samples, experiments conducted on strip steel samples with a flat sensor design produced similar EM responses with the rod samples [5]. The electromagnetic field created by the EM sensor is sensitive to any variations in the electrical conductivity and magnetic permeability of the sample resulting in changes in the complex trans-impedance value recorded. This is particularly useful because conductivity and permeability are known to be directly influenced by the steels' microstructure and carbon content [6]. Austenite is paramagnetic whereas ferrite, pearlite, martensite and bainite are ferromagnetic below \( T_c \). Previous experimental work has shown that the electromagnetic measurements can be severely affected by the presence of a decarburised ferrite layer at the surface of the steel sample [1-5].

Fig. 1a shows the imaginary trans-impedance signal recorded for a high carbon steel sample during slow cooling. The microstructure of the sample consists solely of pearlite. For the cooling rate employed (3°C/min) pearlite starts forming at ~681°C, therefore, the initial abrupt increase seen in trans-impedance value at \( T_c \) is purely due to the presence of a decarburised ferrite layer. Nonetheless, repetitive EM tests on high carbon steel samples and associated metallographic analysis showed that oxidation of the decarburised layer has a diminishing effect on the initial trans-impedance response during subsequent heating cycles [1-4]. As seen in Fig. 1b the thickness of the decarburised layer reaches a maximum during the 2nd heating cycle, which accounts for the high initial trans-impedance response observed at \( T_c \). However, during subsequent heating, the decarburised ferrite layer begins to oxidise, resulting in a reduction of its thickness and hence in a lower initial trans-impedance response as seen in Fig. 1b for the 3rd and 4th heating cycles.

![Figure 1](image_url)

**Figure 1.** Imaginary trans-impedance-temperature responses for: (a) a decarburised high carbon steel sample after 1 cycle at frequency 2 Hz and (b) for a high carbon steel sample during 4 heating cycles at frequency 2 Hz.

3. Finite Element Analysis (FEA) methodology

FE simulations using the Maxwell 2D software package by Ansoft have been conducted to model the effect of the presence of a decarburised surface ferrite layer in a high carbon steel samples on the trans-impedance value.

The sample was represented by a 20 x 20 grid of equilateral hexagonal cells that were defined either as paramagnetic, i.e. representing austenite with a relative permeability (\( \mu_r \)) of 1, or ferromagnetic, i.e. representing bulk ferrite with a \( \mu_r \) of 50, or ferrite in the area affected by decarburisation with a varying \( \mu_r \) of 100, 200 and 500. The reason for which the value of \( \mu_r \) of the
decarburised ferrite was varied is because it is well known that as carbon content decreases in steel its conductivity ($\sigma$) and initial $\mu_R$ increase [6-7]. It is noted that for the simulations initial relative permeability values were employed.

In order to model the extent of the effect of decarburisation it was necessary to use higher $\mu_R$ values so as to represent a higher amount of decarburisation. The length of each side of a hexagonal cell was 2 $\mu$m, thus the total length of the grid was 120 $\mu$m and the total width 80 $\mu$m. The background was taken to be a vacuum with a $\mu_R$ of 1 and $\sigma$ of 0 Sm$^{-1}$. The sensor was represented by two rectangular conductors, which form a coil, defined to be made of copper, with $\sigma$ being $5.8 \times 10^7$ Sm$^{-1}$ and $\mu_R$ of 0.99991. The conductivity of the bulk microstructure of the sample was defined to be $1.1 \times 10^6$ Sm$^{-1}$; simulation trials using varying $\sigma$ values within the temperature range of interest (i.e. 600°C - 800°C) for the specific size of the sample employed for the simulations, determined that the effect on the trans-impedance values was negligible [1-3]. It should be noted here that increases in $\sigma$, during the steel cooling process, have a lowering effect on trans-impedance value, but the extent of the effect is related to the size of the sample. This is not depicted on the FEA results due to the small sample area being simulated.

For a sample of similar size to the ones used during experimentation at low operating frequency (i.e. 2 Hz), $\sigma$ increases have been seen to cause a slight steady decrease in trans-impedance response with temperature as shown in Fig. 2a for a low carbon steel. Experimental results have also shown that the effect of conductivity can be enhanced as sampling frequency increases as seen in Fig. 2b for an operating frequency of 5 kHz. The depth sampled by the sensor at any operating frequency is dependent on the $\sigma$ and $\mu_R$ of the sample at temperature, T. The magnitude of the magnetic field decays following an approximately exponential relationship with depth from the surface [1-3]. Therefore, in any decarburised area that may exist, where the carbon content is decreased, the $\sigma$ and $\mu_R$ of that area will be higher, resulting in a stronger eddy current effect and smaller sampling depth for any given frequency.

![Figure 2](image-url)

**Figure 2.** Electromagnetic response for a low carbon steel sample at: (a) frequency 2 Hz and (b) frequency 5 kHz.

For the simulations discussed hereby, the frequency used was 50 Hz whilst the microstructural patterns employed for the simulations were chosen in such a way so as to represent the decarburised layer. The purpose of the simulations discussed in the present paper was to determine the effect of the formation of a decarburised ferrite layer before and after the bulk phase transformation has been completed and additionally, to model the influence of oxidation of the decarburised ferrite layer with regards to the sensor response.
4. Modelling the decarburisation effect

Fig. 3a,b show the flux lines for a high carbon steel sample without the effect of decarburisation during a) the paramagnetic and b) ferromagnetic state. It is clearly seen that the flux remains undisturbed when the sample is paramagnetic. Hence, the trans-impedance, $z''$, value is at its minimum, i.e. $4.138 \times 10^{-7}$ Ohms. However, in the case where the sample is in the ferromagnetic state (relative permeability, $\mu_r = 50$) the trans-impedance reaches a maximum value of $5.021 \times 10^{-7}$ Ohms. To model the effect of decarburisation before and after phase transformation has been completed, one row of cells in each side of the grid, namely the top and bottom rows, were defined as ferromagnetic with $\mu_r = 100$ and $\sigma = 1.2 \times 10^6$ Sm$^{-1}$, with the rest of the sample defined as a) paramagnetic and b) ferromagnetic. The first case simulates the decarburisation effect prior to the phase transformation of the sample but below the $T_c$, whilst the second case simulates the decarburisation effect after the phase transformation of the sample has been completed.

![Figure 3. Simulation of the EM field flux lines for a) a completely paramagnetic sample and b) a completely ferromagnetic sample.](image)

Fig. 4a and 4b show the differences in the magnetic flux lines for each case respectively. The trans-impedance value for the paramagnetic sample with the ferromagnetic decarburised layer present was found to be $4.742 \times 10^{-7}$ Ohms. This accounts for almost 70% of the total signal indicating the dominant effect that the presence of a uniform decarburised ferrite layer has on the EM response obtained. In the second case, Fig. 4b, for the sample being ferromagnetic ($\mu_r = 50$ and $\sigma = 1.1 \times 10^6$ Sm$^{-1}$) and with the decarburised layer also being present, the calculated trans-impedance value is $5.0261 \times 10^{-7}$ Ohms, which is slightly higher than the value found for the 100% ferromagnetic sample without the presence of the decarb layer. The calculated values for trans-impedance obtained through the aforementioned FE model are in agreement with the experimental results shown in Fig. 1b, as trans-impedance is seen to be approximately the same for all testing cycles after phase transformation has been completed regardless of the thickness of the decarburised ferrite layer present.

Excessive decarburisation of the sample can result in a thick ferrite ring with high $\mu_r$ and $\sigma$ being formed around the sample. In some cases during experimental testing such thick ferrite rings were present with a mean thickness in excess of 150 μm. Furthermore, the mean depth of the sample affected by decarburisation reached up to 600 μm in thickness [1]. Therefore, the decarburisation affected area would exhibit variations in conductivity and relative permeability throughout its thickness due to non-uniform concentrations of carbon throughout the decarburisation affected area, i.e. very low concentrations of carbon are present in the ferrite ring but higher amounts of carbon exist as depth increases [6-7]. In order to simulate the effect of such extensive decarburisation in the present simulations, three rows from the top and three rows from the bottom side of the grid were
assigned with higher $\mu_r$ and $\sigma$ values as shown in Fig. 5a. $\mu_r$ and $\sigma$ were varied for each row in order to simulate the gradual attenuation of the decarburised layer, hence for the first top and first bottom row $\mu_r = 500$ and $\sigma = 1.7 \times 10^6$ Sm$^{-1}$, for the second top and second bottom row $\mu_r = 200$ and $\sigma = 1.3 \times 10^6$ Sm$^{-1}$ and for the third top and third bottom row of cells $\mu_r = 100$ and $\sigma = 1.2 \times 10^6$ Sm$^{-1}$. The rest of the sample was defined as ferromagnetic with $\mu_r = 50$ and $\sigma = 1.1 \times 10^6$ Sm$^{-1}$. The trans-impedance value for the above configuration was found to be $5.054 \times 10^{-7}$ Ohms which is again only slightly higher than the value obtained for the 100% ferromagnetic sample without the decarburised layer present. However, experimental results have shown that after decarburisation has reached a maximum (i.e. carbon has been depleted from the outer region of the decarburised layer) during subsequent heating cycles oxidation of the ferrite ring will begin resulting in the formation of an oxide layer (scale) in its place [1-4]. The oxide layer is paramagnetic at the temperature of interest ($\mu_r = 1$) and has a very low conductivity [7]. To model the oxide effect the aforementioned configuration was employed, however in this case the first top and first bottom row of cells have a $\mu_r = 1$ and $\sigma = 0.1$ Sm$^{-1}$ so as to represent the oxide layer. The $\mu_r$ and $\sigma$ values for the second and third top and bottom rows of cells, and the rest of the sample, remain the same as for the aforementioned simulation. The trans-impedance value for this simulation, shown in Fig. 5b, was found to be $4.992 \times 10^{-7}$ Ohms.

This value is slightly lower than the one obtained for the 100% ferromagnetic sample without any decarburised layer present and again is in agreement with the experimental results in Fig. 1b. Despite the fact that oxidation is seen to have a negligible influence on trans-impedance after phase transformation is completed, it has been shown through the experimental results that prior to the phase transformation it does influence the initial trans-impedance response [1-3]. In order to further support the above statement, the latter simulation was repeated, however, in this case the bulk part of the sample was defined to be paramagnetic (i.e. $\mu_r = 1$) so as to model the effect of oxidation on the trans-impedance value before the phase transformation has occurred. The calculated value for trans-impedance for this simulation was $4.86 \times 10^{-7}$ Ohms which is significantly lower in comparison with
the calculated value for the previous simulation. The effect of oxidation is further enhanced if part of the rest of the decarburisation affected area is also oxidised as shown in Fig. 6. For the simulation shown in Fig. 6 the second top and bottom rows have also been defined to be oxide, i.e. $\mu = 1$ and $\sigma = 0.1 \text{ Sm}^{-1}$ and the calculated value for trans-impedance is $4.71 \times 10^{-7}$ Ohms. From the aforementioned results it is seen that oxidation influences the trans-impedance response depending on its extent. The decarburisation effect is also enhanced by its extent but as it has been discussed in past papers distribution i.e. connectivity of the decarburisation affected zone is the critical factor that influences the EM response [1-3].

![Figure 6](image.png)

**Figure 6.** Simulation of the EM field with 2/3 of the decarburisation affected zone having oxidised and with the rest of the sample being paramagnetic.

5. **Conclusions**

The present paper summarises the effects of decarburisation and oxidation on the imaginary trans-impedance response of an EM sensor designed to detect phase transformation in steel during cooling. FE simulations have been employed in order to model the influence of decarburisation and oxidation on the EM signal. It has been shown that decarburisation is a major factor prior to the phase transformation but its effect diminishes after transformation is completed. In addition, the oxidation effect after phase transformation is completed has been modelled and seen to have a negligible impact. However, prior to the occurrence of the bulk phase transformation oxidation of the decarburised ferrite layer has a major influence on the initial trans-impedance response which is dictated by the extent of the oxidised volume as shown in the simulations.

6. **Acknowledgements**

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