Magnetic NDT for Steel Microstructure
Characterisation – Modelling the Effect of Second Phase Distribution on Magnetic Relative Permeability

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Abstract. Strip steels with a dual-phase (DP) or complex-phase (CP) microstructure are widely used in the automotive industry. The microstructure of these steels consists of ferrite with typically 20-80\% dispersion of second phase (predominantly martensite or bainite) islands, depending on the grade. In order to obtain accurate quality control, it is important to be able to monitor the mechanical properties of the product non-destructively and this may be achieved by measurement of the volume fraction and spatial distribution of the phases as there is a direct link between microstructure and mechanical properties. Electromagnetic (EM) techniques are a viable method for quantitative characterisation of the phases and are non-contact, have a short response time and are relatively inexpensive. EM sensors such as EMSpec, operating at a low applied low field, are sensitive to the initial relative permeability of steel, which depends on the microstructure. Previously, the effect of ferrite fraction (in ferrite – pearlite and ferrite - austenite steels with uniform second phase distribution) on the relative permeability was modelled using a 2D finite element (FE) microstructure – EM model using COMSOL Multiphysics. The microstructural phases were considered as constituents with different relative permeability values.

In this paper, the modelling is extended to 3D microstructures considering the influence of the second phase type and spatial distribution on relative permeability. Simulated 3D microstructure models with different second phase amount, type and distribution were generated, using a voronoi based algorithm (Multi Level Voronoi), which provides a parametric description of the phase type, and contiguity in a grid format. Magnetic relative permeability values were predicted for these microstructure models and validated for selected microstructures. It has been found that 3D modelling gives higher values of relative permeability for a given ferrite fraction than the 2D models (up to 16\% difference) due to the added degree of freedom in magnetic flux flow. It was also found that there is a significant difference in permeability values from the direction of the field with respect to the orientation of any second phase banding in the microstructure.
1. Introduction

Strip steels with a dual-phase (DP) or complex-phase (CP) microstructure are widely used in the automotive industry. The microstructure of dual phase steels consists of ferrite with 20-80% dispersion of second phase (e.g. martensite, tempered martensite and/or bainite) islands. The microstructure is produced either by controlling the transformation of austenite after hot rolling or by heat treatment after cold rolling. The amount and type of any second phase plays an important role in determining the mechanical properties. In order to achieve accurate control of the steel quality, in particular of the mechanical properties, during manufacturing, it is important to be able to monitor non-destructively the volume fraction and spatial distribution of the phases as there is a direct link between microstructure and mechanical properties. Several techniques could be employed such as X-ray, electromagnetic or ultrasonic sensors [1-4]; among which, electromagnetic (EM) techniques have attracted much attention due to their advantages of being non-contact, having a short response time and being relatively inexpensive [5].

EM sensors such as EMSpec [6], operating at a low applied low field, exploit the difference in electromagnetic properties, such as relative permeability and electrical conductivity, between samples with different microstructural phase balances. In ferromagnetic steels, the magnetic properties have a stronger dependence on the metallurgical phase balance than the electrical conductivity, particularly at low frequency where eddy currents are small [7]. Previously, multi-frequency EM sensors have been shown to be able to measure austenite/ferrite fraction from 0% to 100% in model (HIPped austenitic-ferritic stainless steel powder) alloys [8, 9] and ferrite-pearlite steels with uniform second phase distribution in C-Mn steels with different carbon contents [10]. EM sensors have also been used to measure the levels of decarburisation (variation in ferrite content with depth) in high carbon steel rod and rails [11-13]. The approach adopted to relate the overall steel EM sensor signal to its microstructure involves two steps. The first step is to model the effective relative permeability for the microstructure; and the second step is to link the effective relative permeability to the sensor output using a finite element (FE) sensor output model with the particular sensor geometry. In this way different microstructures and sensor designs can be considered separately or in combination.

When considering the effective electrical or magnetic property of a material, which has two components with contrasting properties, the effective medium theory is usually used. The principle of the effective medium theory is that the electrical/magnetic potential due to the mixture placed in the external electrical/magnetic field is equal to the potential caused by a geometrically identical object having an effective conductivity/permeability/permittivity. Empirical based power law models have been popularly used [9, 14-16]. The power law model predicts the effective permeability as

\[ \mu_e^\beta = (1 - f)\mu_1^\beta + f\mu_2^\beta \]  

(1)

Where \( \mu_1 \) and \( \mu_2 \) are the relative permeability values of the first and second phase respectively, \( f \) is the fraction of the second phase, and \( \beta \) is a dimensionless parameter. Examples of the power law are the Birchak formula (\( \beta = 1/2 \)) [16] and the Looyenga formula (\( \beta = 1/3 \)) [15] for prediction of the dielectric constant of mixtures.

Hao et al. developed a FE microstructure model to predict the relative permeability based on actual microstructures. The microstructural phases were considered as constituents with different relative permeability values. The FE microstructure model was found to give good agreement with measured results over the whole range of ferrite fraction for austenite/ferrite microstructures. However, the power-law model with \( \beta = 1/2 \) did not give a good fit, whilst \( \beta = 1/3 \) only gave good agreement with measured results at ferrite fractions above 40% (samples with ferrite fractions below 40% would require a much smaller \( \beta \) value to give good fitting) [9]. Using the same FE modelling approach, Zhou et al. modelled the
effect of ferrite fraction on the relative permeability in ferrite/pearlite steels with uniform second phase distribution [10]. It was reported that the shape of the permeability-ferrite fraction relationship in ferrite/pearlite microstructures is different than for ferrite/austenite due to the fact that the magnetic flux pathway is less affected by the second phase when the latter is ferromagnetic (e.g. pearlite, bainite, martensite and/or tempered martensite), than when it is paramagnetic (austenite) [10]. To date the FE microstructure modelling to predict magnetic relative permeability has only been carried out in two dimensions (2D), whereas the electromagnetic field generated by the EM sensor interacts with the microstructure in three dimensions (3D), therefore it is important to study how the permeability-ferrite fraction relationship changes when the modelling is carried out in 3D. In addition, 3D modelling allows non-uniform microstructures to be fully considered, for example banded microstructures are commonly seen in many commercial steel grades due to chemical composition segregation during casting which is retained during the subsequent rolling process. It was reported that this anisotropy in microstructure can affect the effective permeability in a ferrite-austenite microstructure, although only 2D simulations were performed [9], and it has been shown that when an EM sensor is used to measure a rolled plate, with a banded ferrite-martensite [17] or ferrite-austenite [14] microstructure, signal responses can be different for measurements in the longitudinal and transverse orientations.

In this paper, the modelling of the effect of 2nd phase on the effective magnetic relative permeability has been extended to 3D microstructures using simulated microstructure models. The effect of banded microstructures and the significance of the second phase type, amount and spatial distribution on the relative permeability, and hence EM sensor signals, for non-destructive characterisation of two phase steels is discussed.

2. Modelling method

Simulated 2D and 3D microstructure models with different second phase amount, type and distribution were generated, using an advanced voronoi based algorithm (Multi Level Voronoi) [18, 19], which provides a parametric description of the phase type and contiguity in a grid format. Grid format data for two phase microstructures with ferrite fraction of 0-100% with 5% steps were provided by Tata Steel Europe. An initial study on the effect of grid size (number of pixels in the x, y or z directions, which is a reflection of the resolution of the microstructure model) for the 2nd phase distribution and its effect on the modelled permeability was carried out, considering grid sizes of 50, 100 and 200. An increase in grid size affects the time required to solve the FE model, therefore the minimum grid size to give sufficient resolution is optimum. It was found that the grid size affects the connectivity of the ferrite in the microstructure model, which is known to impact the FE modelled permeability value [14]. The predicted relative permeability value for 50% ferrite + 50% austenite phase, at which the relative permeability value is found to be most sensitive to 2nd phase distribution, decreases from 48 to 38 and to 34 with grid size increases from 50 to 100 and to 200. A further increase in grid size would increase the computation time considerably (each model takes approx. 72 hours at a grid size of 200) and is only expected to decrease the predicted relative permeability value by less than 4, which is equivalent to <1.2% error in the model across the full range of ferrite fractions. Therefore, a grid size of 200 was chosen for all 2D and 3D microstructure models, in order to minimise any increase in connectivity caused by low resolution. Each simulated microstructure model has 1000 grains, with defined materials property of phase type at each pixel.

Magnetic relative permeability values were predicted for these microstructure models. The 2D FE microstructure - permeability model used in this study is similar to that used by Hao et al with conditions that the top and bottom boundaries of the sample were set with a magnetic potential of 1 and 0, respectively, to generate a uniform horizontal magnetic field. The left and right boundaries of the sample were set as electric insulation (magnetic
field normal to the boundary) to eliminate the demagnetising field, this is termed “condition 2” as described in [9]. In the 3D FE microstructure-permeability model, a 200×200×200 μm block is placed in an external magnetic field of 1 A/m. The materials properties at each pixel in the simulated 2D or 3D microstructure model were linked with their 2D or 3D coordinates and exported as csv files using MATLAB. The csv files were imported into the FE model by the COMSOL built-in interpolation function and the “spatial coordinates” were set as the local material property (relative permeability). Relative permeability values of 330, 58, 1 are assigned to ferrite, pearlite and austenite respectively, measured for single phase microstructures using a cylindrical EM sensor and determined from a sensor-sample model [10]. These values are assumed to remain constant for the specified applied field within the FE model.

In order to model the effect of a real banded microstructure for a commercial grade steel sample, SEM micrographs from commercial DP600 steel (with a ferrite/martensite microstructure) were converted to black and white binary images and imported into the COMSOL model, with the relative permeability of ferrite and martensite set as 330 and 80 respectively. The relative permeability for martensite (as a single phase) was also determined using the cylindrical sensor [17].

The relative permeability of the two phase microstructure was calculated using parameters derived within the COMSOL software:

$$\mu_r = \frac{B_{ave}}{\mu_0 H_{ave}}$$  \hspace{1cm} (2)

Where $B_{ave}$ is the average flux density inside the sample, $\mu_0$ is the permeability of free space, and $H_{ave}$ is the average magnetic field inside the sample.

3. **Effect of ferrite fraction on relative permeability - 2D versus 3D models**

The 2D and 3D modelling results for the effective relative permeability variation with ferrite fraction in the ferrite-austenite and ferrite-pearlite (which will be similar to ferrite-martensite) steel samples are shown in Fig. 1. Note that the ferrite and second phase are randomly distributed. In general, the relative permeability values increase with ferrite fraction due to the much higher permeability value of ferrite in comparison with the permeability of the 2nd phases. The 3D modelling predictions give higher relative permeability values than for 2D modelling, as the magnetic flux lines have one more degree of freedom to pass through the sample. Previous experimental results for EM sensor measurements of DP and CP steels showed a close to linear relationship between inductance (which can be correlated to relative permeability) and ferrite fraction (samples with 24% - 86% second phase) [17], which is more similar to the 3D model results. In addition, the 3D modelling results show a closer fit, over the full range of 0% - 100% second phase, with the experimentally obtained relative permeability values in ferrite-austenite microstructures reported in [9]. Therefore, it can be stated that, compared to the 2D modeling, the 3D modelling results have a better agreement with the measured values for both the ferrite-pearlite/martensite and ferrite-austenite microstructures.

It was observed that the effect of low ferrite volume fractions on the relative permeability values for ferrite-pearlite microstructures is more significant than for ferrite-austenite microstructures. This is because pearlite is ferromagnetic at room temperature, therefore when the ferrite fraction is low (ferrite grains are isolated), the magnetic flux can more readily pass through pearlitic regions between the preferred ferrite regions, whereas the austenite phase, being paramagnetic, is less favourable, hence a more complex route between ferrite regions occurs, to minimize passage in austenite (shown in Fig. 2).
Fig. 1. 2D and 3D modelling results for the effective relative permeability variation with ferrite fraction in the (left): ferrite-austenite and (right): ferrite-pearlite steel microstructures.

Fig. 2. FE modelled results of magnetic flux distribution for microstructures with 30% ferrite in (left) ferrite-austenite phase balance and (right) ferrite-pearlite phase balance. Stream line: magnetic flux density.

4. Effect of 2\textsuperscript{nd} phase distribution on relative permeability

4.1 Modelling the effect of 2\textsuperscript{nd} phase distribution on permeability in 3D microstructures

In order to study how much a banded 2\textsuperscript{nd} phase microstructure can affect the effective permeability value, three 3D microstructure models with 20% 2\textsuperscript{nd} phase but different spatial distributions were generated to represent random, extremely banded, and a microstructure with complex morphology of ferrite grains with 2\textsuperscript{nd} phase particle only at the grain boundaries (on the average diameter of the ferrite grains is five times the 2nd phase ones). It is expected that the microstructure especially for higher volume fraction of 2\textsuperscript{nd} phase the particles will form a closed network. Representative images from each of the microstructure models are given in Fig. 3.

Fig. 3. 3D microstructure models to represent random, extremely banded, and a complex morphology microstructure for two phase steels. 2\textsuperscript{nd} phases are shown in black colour.
The modelled effective permeability results for the magnetic field oriented along the x, y or z directions for the simulated 3D microstructure models are summarised in Table 1. It can be seen that for the random distribution model, as expected, the modelled effective permeability values in the three directions are almost equal (within 1% difference).

**Table 1.** The modelled effective permeability (Mur) results along x, y and z directions for simulated 3D microstructure models with a 20% volume fraction of the second phase.

<table>
<thead>
<tr>
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<th>Random distribution</th>
<th>Extremely banded distribution</th>
<th>Complex morphology</th>
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<tbody>
<tr>
<td></td>
<td>Ferrite / Martensite</td>
<td>Ferrite / Martensite</td>
<td>Ferrite / Martensite</td>
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<tr>
<td>Mur along x direction</td>
<td>250</td>
<td>247</td>
<td>253</td>
</tr>
<tr>
<td>Mur along y direction</td>
<td>252</td>
<td>249</td>
<td>254</td>
</tr>
<tr>
<td>Mur along z direction</td>
<td>253</td>
<td>210</td>
<td>252</td>
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In the complex morphology microstructure model, there is no significant effect of 2nd phase morphology on the relative permeability for the ferrite-martensite microstructure, however the ferrite-austenite structure shows sensitivity to the austenite morphology. The slight elongation of the austenite in the x and y directions means that when the flux flows in the z orientation the permeability is reduced, whilst the permeability values in the x and y directions show no difference to the random distribution condition. This occurs because the magnetic flux is forced to deviate more to find preferential pathways through ferrite in the z direction, whilst little deviation occurs when the 2nd phase is pearlite as it is ferromagnetic.

In the complex morphology microstructure model, there is no significant effect of 2nd phase morphology on the relative permeability for the ferrite-martensite microstructure, however the ferrite-austenite structure shows sensitivity to the austenite morphology. The slight elongation of the austenite in the x and y directions means that when the flux flows in the z orientation the permeability is reduced, whilst the permeability values in the x and y directions show no difference to the random distribution condition. This occurs because the magnetic flux is forced to deviate more to find preferential pathways through ferrite in the z direction, whilst little deviation occurs when the 2nd phase is pearlite as it is ferromagnetic.

In the extremely banded microstructure model, for the ferrite-martensite phase balance, the effective permeability in the z direction is lower than in the x and y orientations, as the magnetic flux passes through significant amounts of martensite phase when penetrating the sample. Although the same effect would also be expected in the ferrite-austenite phase balance, the modelling results show this is not seen. The predicted permeability in the x and y directions are also significantly lower than that of a random 2nd phase distribution. As can be seen in Fig. 4 (left), the small fraction of ferrite within the 2nd phase band has little connectivity therefore it does not contribute to any significant increase in permeability value for this band (see Fig. 1 for the small change in permeability for low ferrite fractions in ferrite+austenite microstructures), hence the effective permeability of the central band containing the second phase (which accounts for approximately 30% of the overall microstructure) is effectively very low. The model then predicts a similar relative permeability value for the overall microstructure to the result obtained for a random microstructure with 30% austenite as 2nd phase, Fig. 1. It can be seen in Table 1 that the predicted relative permeability values for the x, y and z orientations are very similar. This is because the 2nd phase band in the z direction is thinner, and there is connectivity of ferrite in
the z orientation through the band in 3D (shown in Fig. 4 (right)), therefore the effect of the band is less significant.

4.2 Modelling the effect of 2nd phase distribution on permeability using real microstructure

The effect of banded microstructures in commercial grade steels has been considered by importing SEM micrographs from DP800 steel with a ferrite-martensite microstructure. Fig. 5 shows the modelled effective permeability results and the flux distribution for magnetic fields applied parallel and perpendicular to this microstructure. It can be seen that the orientation of the applied field to the banded microstructure has a significant effect on the modelled relative permeability value. This agrees with the previous study using an H-shaped EM sensor to make measurements on DP steels which showed the low frequency (at 100Hz) real inductance values measured by placing the sensor perpendicular to the rolling direction are consistently slightly lower than the ones measured parallel due to the elongation of the grains and banded second phase [17]. It was reported that the measured DP800 EM sensor signal gives a change of $1.3 \times 10^{-5}$ H in inductance, which would be equivalent to about 10% change in ferrite fraction prediction for these steels which contain ferrite in the range of 70-90% [17]. Using the 2D modelling results presented in Fig. 1, a 10% change in ferrite fraction in this range would be equivalent to a relative permeability change of about 41. This is close to the predicted permeability change of 44 (226 – 182) modelled by the 2D FE microstructure - permeability model using the actual microstructure.

The modelling for this real microstructure has only been carried out in 2D as, presently, only 2D real microstructures can be imported into the FE microstructure - permeability model. Further 3D simulations will be done using representative microstructure models such as depicted in Fig 3.

Fig. 5. The modelled effective permeability (Mur) results and flux distribution in a DP800 steel microstructure. Left: SEM image showing phase distribution of ferrite (dark) and martensite (bright); middle: modelled magnetic flux distribution when horizontal and, right, vertical magnetic fields are applied.

4.3 Summary

The results above suggest that the 2nd phase distribution must be considered in order to avoid relative permeability values, and hence ferrite fractions, being over or under-estimated based on the orientation of the sensor (and hence magnetic field) with respect to (directionality in) the microstructure. This is particularly relevant for situations where the composing phases have largely separated magnetic permeability, i.e. ferrite and austenite phase mixtures. These occur in duplex stainless steel or during the austenite to ferrite transformation at high temperatures in regular structural steels, as the permeability of ferrite phase increases significantly with temperature [20], while the austenite phase is paramagnetic across the whole temperature range.
5. Conclusions

In this paper, the effect of 2nd phase type, fraction and distribution on relative permeability were modelled by a FE microstructure - permeability model in both 2D and 3D. The effect of phase fraction on the modelled relative permeability for both ferrite-austenite and ferrite-pearlite over 0 – 100% range are shown. The results of 3D modelling predict higher relative permeability values than for 2D modelling, as the magnetic flux lines have one more degree of freedom to pass through the sample. Previous experimental results suggest that 3D modelling results predict a more accurate trend for the ferrite-pearlite/martensite and ferrite-austenite phase balance.

The effect of 2nd phase distribution (i.e. banding effect) was studied in both 2D and 3D microstructure - permeability models. It was shown that a significant difference in permeability values result from the direction of the field with respect to the orientation of the 2nd phase banding. Therefore, the 2nd phase distribution must be considered in order to correctly estimate the relative permeability values for phase balance characterisation.

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References