Non-Destructive Measurement of Microstructure and Tensile Strength in varying thickness commercial DP Steel Strip using an EM Sensor

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Abstract. It is desirable to be able to non-destructively evaluate the microstructural features and/or mechanical properties of steel strip. An electromagnetic sensor – sample FE model, developed in COMSOL multi-physics software, has been developed to determine the relationship between the low magnetic field relative permeability and microstructure (phase balance and grain size), and hence tensile strength, for commercial dual phase (DP) steel sheets of any thickness. The model for the effect of thickness on the sensor signal has been validated using DP steel sheets of 1 to 4 mm. It was found that the relative permeability is strongly dependent on the phase balance (fraction of ferrite and martensite) in the DP steels with an increasing relative permeability being seen for a higher fraction of ferrite. In addition, changes in the ferrite grain size also affect the relative permeability (increase in grain size increases relative permeability) and hence EM sensor signal, this being more significant for the higher ferrite content DP grades. Both these microstructural features affect the tensile strength (which decreases with an increase in ferrite fraction and increase in grain size), which results in a good correlation between the relative permeability and tensile strength. The results from the relative permeability – microstructure – tensile strength investigation and FE model to account for strip thickness have been combined to allow the prediction of tensile strength from EM sensor measurements on as-received commercial DP steel sheets of varying thickness and the approach has been tested.

Keywords. Electromagnetic sensor, relative permeability, ferrite fraction, tensile strength, non-destructive testing

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1. Introduction

The increasing demands for lightweight, crashworthiness and high performance in the automotive industry means that improved steel grades are required. There has been growing attention to the manufacturing of dual phase (DP) steels for their high strength accompanied by light-weighting of automotive components [1]. DP steels are characterised by a combination of ferrite with typically 20-80% as a soft matrix that provides good elongation and a dispersion of second phase (e.g. martensite, tempered martensite and/or bainite) giving the high strength. This unique microstructure offers a combination of continuous yielding behaviour, good formability and high tensile strength [2, 3]. The mechanical properties of DP steel are strongly influenced by its microstructural parameters, in particular phase balance and grain size [4-6]. A variety of techniques can be used to characterise the microstructure, the most frequently used are optical microscopy and scanning electron microscopy (SEM) on polished and etched samples. These conventional methods to obtain phase and grain size information are destructive, and time consuming, as they require a small piece of material to be removed from the strip / component. Multi-frequency electromagnetic (EM) sensors are sensitive to both changes in relative magnetic permeability and resistivity of steel, with the low frequency inductance values being directly related to the permeability. In recent years the use of magnetic techniques, based on EM sensors, for non-destructive testing has increased [7-10]. Previously EM sensors have been shown to be able to monitor the transformation from austenite to ferrite, below the Curie temperature, and to distinguish between samples with mixed microstructures (ferrite + austenite; ferrite + pearlite; ferrite + martensite) across the whole range of ferrite percentages [11, 12]. EM sensors can be used to characterise austenite and ferrite fraction in hot strip mills (EMspec^{TM} system

[13]) and for statistical correlations to mechanical properties (IMPOC and HACOM systems [14]) in cold strip mills. It is desirable to be able to determine both microstructural and mechanical property information about steel strip, which requires models capable of relating the magnetic signals to microstructure as well as tensile strength. Tensile strength data is required to ensure the steel meets customer requirements whereas the microstructure data gives more specific information on how the processing schedule has developed those properties and could be further optimised. A laboratory U-shaped EM sensor has been used to characterise the phase fraction in DP steels, with verification previously shown for DP structures within the range of ferrite fraction from 35-72% with consistent grain size using samples of constant thickness [15]. As there are known relationships between the microstructure of DP steels with tensile strength [4-6, 16], the EM signals can therefore be used to determine strength and/or hardness. Previous work has established finite element (FE) based models to relate the microstructure (phase balance) to the magnetic property of low field permeability, allowing the microstructure (ferrite fraction) to be determined from the EM sensor signal [17]. In that work, only single sheet thickness heat treated DP steel samples (varying phase fraction with consistent ferrite grain size) were considered and a full sensor model, which could take into account sample geometry, was not available. Ghanei et al. [18, 19] used eddy current testing (ECT) to predict the mechanical property of DP steel, also for constant thickness samples. In that work a frequency of 250Hz was chosen, by regression analysis, to be the optimum frequency for impedance output correlation to strength. There is also a significant amount of data relating magnetic properties determined from BH curves (e.g. coercivity or permeability) and microstructure or strength / hardness [20-22], but not for deployable sensors that can be used to measure any steel sheet geometry. This paper

reports on the use of a portable EM sensor that can be used for any flat sheet thickness for off line characterising DP steels (microstructure and tensile strength) and the development of a calibration procedure, using a full sensor-sample FE model, to account for strip thickness. Results for tensile strength prediction, including discussion on the effect of the different microstructural features, for a range of commercial DP steels (DP600, DP800 and DP1000) are discussed.

2. Material and methods

A number of commercial DP600, 800 and 1000 grade steels of different thicknesses (1 – 4 mm), supplied by Tata Steel Europe, have been investigated. Metallographic samples were prepared by mechanical polishing using successive polishing steps (to a 0.05µm final surface finish). The polished surfaces of the specimens were etched in Nital 2%. Up to eight optical microscopy images from different locations for each DP sample were taken (from the transverse section) and ferrite percentages were calculated using Image J software.

Vickers hardness testing (Wilson VH1202) was carried out using a 500g load and each sample hardness value was determined by taking the average of ten measurements. Flat tensile specimens of 80mm gauge length and 20mm gauge width were prepared as per ASTM E8M standard; tensile tests were conducted using a Static Instron 100kN testing machine at a strain rate of $0.002s^{-1}$ and stress-strain plots were obtained for each sample. Four repeated tensile tests were carried out for each DP steel. The EM measurements were carried out using a U-shaped multi-frequency EM sensor on sheet samples.

A minimum sheet size of 300 x 80mm was used to avoid edge effects during testing (although this could be accounted for using the FE sensor sample model if required). The minimum size for edge effects was determined for the sensor using a large strip taking measurements progressively closer to the edge. Signal values stabilise at a distance of 80mm from the edge of the sample for the parallel orientation and 20mm for the perpendicular orientation.

The sensor consists of one generating coil with 100 turns of 0.24mm insulated copper wire and two sensing coils with 86 turns of 0.16mm insulated copper wire, which were wound on a ferritic U-shaped core with a bridge of 100mm, leg lengths and thickness of 56mm and 25mm respectively. The EM sensor's excitation coils were driven using an impedance analyser Solartron (SL 1260) with an AC voltage of 3V at frequencies from 1Hz to 10 kHz and measurements of inductance were taken for all samples.

The modelling work for the U-shaped sensor was carried out using COMSOL Multi-physics software using the three dimension FEM (3D) mode in the AC/DC model [23] to study the relationships between sensor signals (real inductance) and relative permeability of the steel sample. The COMSOL modelling approach is based on solving the Maxwell equations and in the model, boundary conditions of the magnetic field, the perfect magnetic conductor and the magnetic insulation were used. The geometry and details of the sensor/sample were set to be the same as the experimental set up (Fig 1). Initial calibration of the sensor model was carried out by fitting the sensor model to sensor measurements over the frequency range 1 Hz – 65 kHz for reference samples of known low field relative permeability and resistivity to account for minor differences between the model and experimental system. The model was then used to determine the low field relative permeability (using the low frequency signal where the effect of eddy currents are negligible) from the measured sensor signal for the samples of interest.

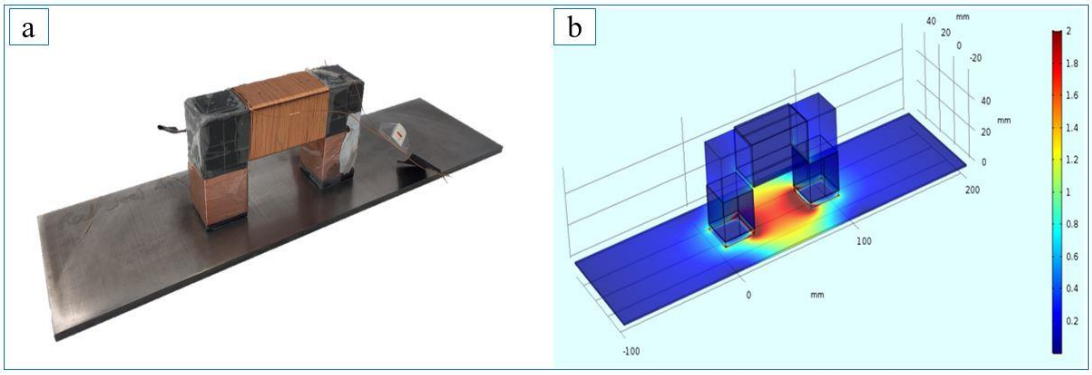

Fig 1. U-shaped EM sensor on the strip sample (a) and U-shaped 3D FE model to estimate the low field permeability of specimens where the colour scale represents the magnetic flux intensity (b).

It is worth mentioning that the applied magnetic field for the U-shaped EM sensor used in this work corresponds to the Rayleigh region (the field is about 500A/m, determined from the sensor sample model and Gauss meter (GM08) readings).

3. Results and Discussion

3.1. Microstructure and mechanical properties

Typical SEM images of the DP600, DP800 and DP1000 steels are shown in Fig 2. As can be seen, the microstructure of dual phase (DP) steels consists of a ferrite matrix containing a second phase in the form of islands (martensite, bainite and/or tempered martensite) [24]. Different volume fractions of ferrite and martensite / bainite are present in the different grades of DP steels, used to give the different strength levels [4, 5, 24]. The presence of martensite/bainite is the main reason for higher tensile strength/hardness of DP samples. The values of ferrite fraction, grain size, tensile strength and hardness are given in Table 1. As can be seen, a decrease in the ferrite phase percentage (or increase in the martensite/bainite percentage) results in an increase in the tensile strength / hardness value of the DP steel samples.

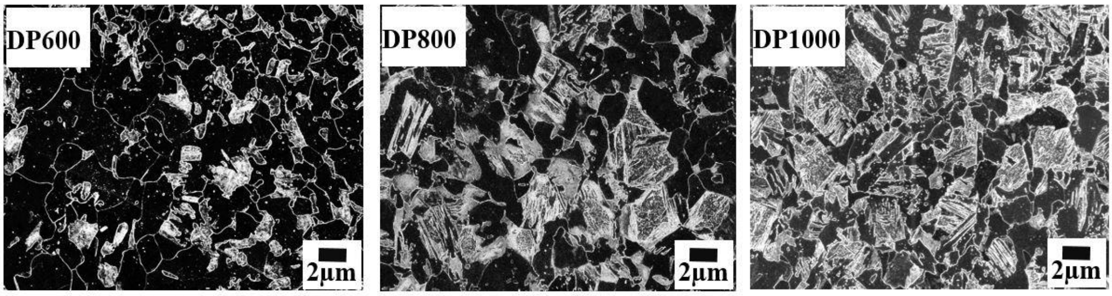

Fig 2. SEM images of commercial DP600, DP800 and DP1000 steels (InLens mode 5KV); the microstructures consist of a ferrite matrix (black) containing a second phase in the form of islands (martensite, bainite and/or tempered martensite).

Table 1. Microstructure, mechanical property and low field relative permeability (determined from the U-shaped sensor model and measured values) of the commercial DP steels. Standard deviation values are given.

Sample ID	Ferrite fraction (%)	Grain size (µm)	Hardness (HV)	UTS (MPa)	Low field relative permeability
DP600CR 1mm	74 ±2	7±3	194±2	684±19	150±3
DP600CR 1mmGl	76 ±2	6±2	190±3	657±25	154±2
DP600CR 1.4mm	72 ±5	7±3	205±5	656±11	146±3
DP600CR 1.5mm	74 ±2	7±2	195±4	670±17	147±2
DP600HR 4mm	79 ±4	10±4	185±4	646±30	177±3
DP800CR 0.95mm	58 ±4	6±3	234±5	762±41	130±2
DP800CR 1.6mm	59 ±5	3±2	240±4	824±48	120±3
DP800CR 1.6mmGl	52 ±1	5±2	234±4	803±14	125±3
DP800CR 2mmA	49 ±2	5±1	244±2	827±15	122±3
DP800CR 2mmB	65 ±2	3±1	255±5	863±38	118±4
DP1000CR 1mm	39±3	3±1	320±6	1074±10	108±2
DP1000CR1.2mmGl	42 ±2	3±1	318±5	1026±15	110±2
DP1000CR 1.6mm	42 ±1	4±2	321±7	1023±20	110±3

HR=Hot-rolled, CR=Cold-rolled, Gl=Galvanized

To determine the relationship between the phase fraction and strength, the ferrite fraction and tensile strength were quantified. The decrease in tensile strength with increasing volume fraction of ferrite for DP steels is well known and widely documented [3, 4, 25]. This is in agreement with the results shown in Fig 3. There is a clear general decrease in the tensile strength with an increase in ferrite fraction for DP grades, which is related to the lower martensite (or bainite) fraction.

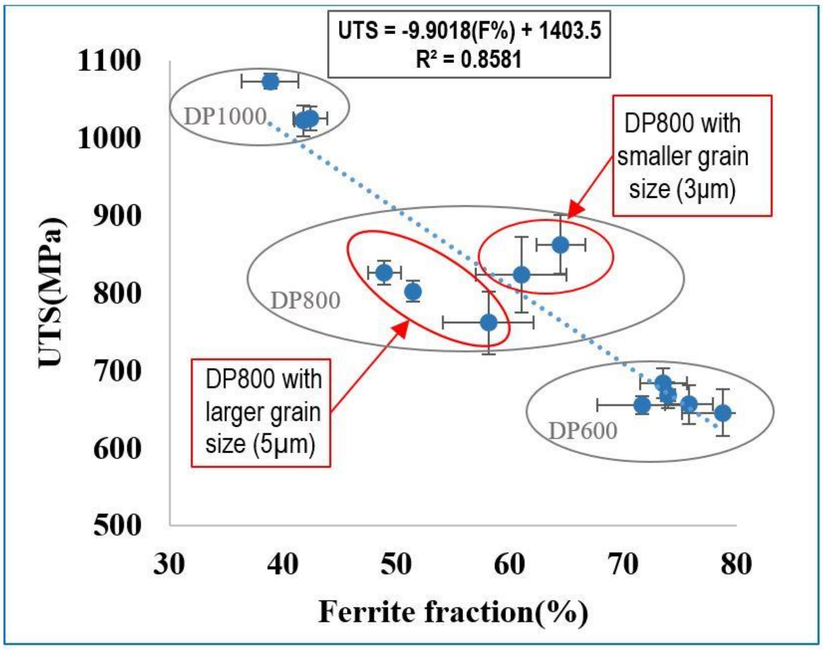

Fig 3. Ultimate tensile strength as a function of ferrite fraction for commercial DP600, DP800 and DP1000 steel; the DP800 samples show more scatter in their relationship, where the higher than expected tensile strength is due to samples with a smaller grain size (3µm compared to 5µm).

The trend between tensile strength and ferrite fraction follows an approximately linear relationship for the DP samples. The trend stems mostly from the composite effect due to the presence of hard particles in a soft matrix. The correlation coefficient for the best fit equation is only R^2 =0.8581 and it can be seen that there could be overlap in ferrite fraction between the grades (e.g. for the DP600 and DP800 grades), therefore ferrite fraction alone is not a good indicator of grade type or tensile strength. In addition, from Fig 3 it can be seen that there is a lot more scatter for the DP800 grades than the other steels. To determine the cause of the scatter, closer examination of their microstructures was carried out and, in particular, the ferrite grain size was investigated. It was found that the scatter can be related to the difference in grain size between the samples (as the DP800 strips came from different mills and hence experienced different processing conditions, which can give different grain sizes), with the samples above the best fit line having a finer grain size than those below the best fit line. The approximately linear relationship between strength and ferrite fraction holds well if the ferrite grain size does not alter between samples, however if ferrite grain size varies then this also needs to be taken into account. It should be noted that for DP1000 material any effect of ferrite grain size variation will be less significant on strength as the ferrite fraction is low (approximately 40% ferrite).

In term of mechanical properties, grain boundaries may act as obstacles to dislocation slip. At room temperature, yield stress (σ_y) depends on the inverse square root of the grain size, i.e. the Hall–Petch relationship [24-28] and also grain size affects the tensile strength [29]. It is known that the ferrite grain size affects the magnetic properties in low carbon steel as the grain boundaries act as effective pinning points to magnetic domain movement [30-32]. Therefore, not only ferrite fraction but also ferrite grain size affects the magnetic properties in DP steels and this has been reported in the literature [33]. The results in Fig 4 show a strong effect of ferrite fraction on the low field permeability, as has been seen previously [15], although the correlation coefficient for the best fit line is low (R^2 =0.8116) as the effect of grain size on permeability is not taken into account. The two DP800 samples with the smaller ferrite grain size show lower permeability values than the other DP800 samples indicating that grain size has a significant effect on the magnetic property (permeability) in these steels as well as ferrite fraction [34].

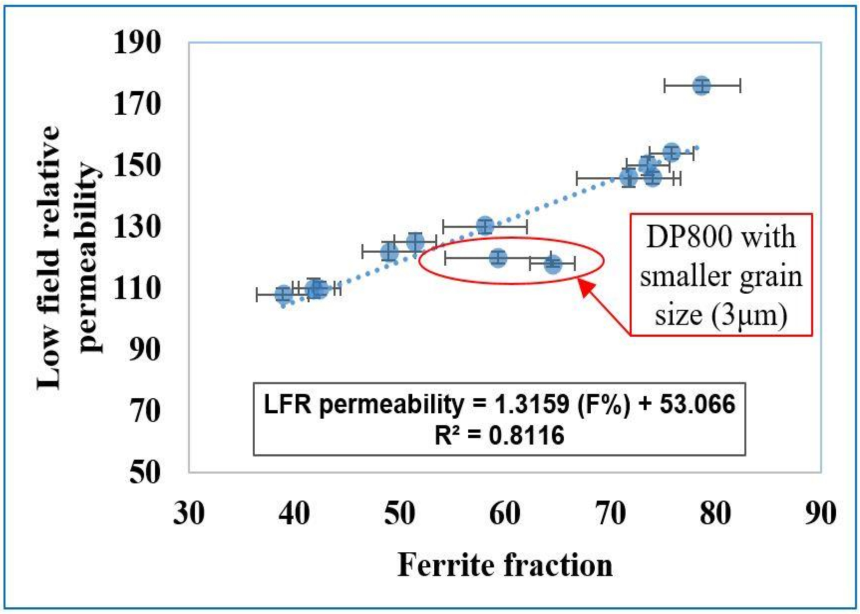

Fig 4. The variation of permeability with ferrite fraction for the DP steel, the marked samples showing lower than expected permeability due to the smaller gain size, (LFR permeability=low field relative permeability).

Since both tensile strength and permeability are affected by ferrite fraction and grain size it might be expected that the two properties will show a strong correlation. The permeability (determined from the U-shaped sensor-sample FE model) is plotted against tensile strength in Fig 5 (and listed in Table 1). The results indicate that there is a general correlation between permeability and tensile strength for the commercial DP steels, i.e. a DP steel with higher volume fraction of ferrite (and/or larger grain size) showing a higher relative permeability and lower tensile strength. The relative permeability value increases with an increase in ferrite fraction due to the lower fraction of magnetically harder martensite, effect of decreased dislocation density (from martensite formation), easier reverse domain formation and domain wall motion taking place at a lower applied field in ferrite [31, 35]. The correlation coefficient for the best fit equation is very high (R^2=0.9696), which shows that the relative permeability is a good measure to predict tensile strength for DP steel samples. In particular Fig 5 shows that there is clear differentiation between the DP600 and DP 800 samples. However, it is noted that differentiation for the samples with lower values of permeability (i.e. DP800 and DP1000) is less. The correlation in Fig 5 is not linear but there is less scatter around a line of best fit than in Fig 4.

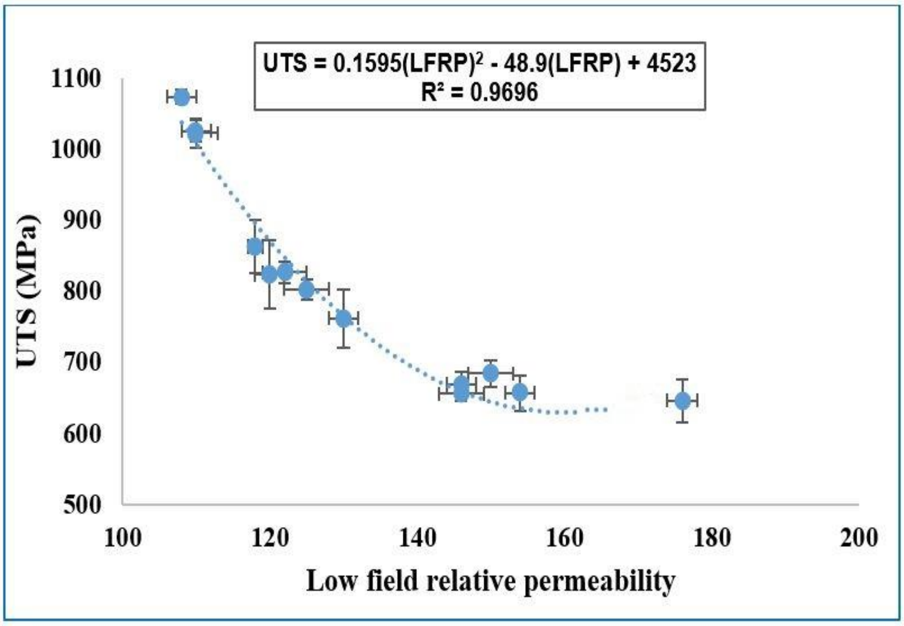

Fig 5. Measured permeability values from the U- shaped sensor-sample FE model for the commercial DP600, 800 and 1000 steels plotted against tensile strength, (LFR permeability=low field relative permeability).

3.2. EM sensor measurements and FE Modelling

The EM sensor output, in terms of inductance versus frequency is shown in Fig.6 for the DP steel samples. The magnetic field produced by a multi-frequency EM sensor acts on a ferromagnetic target in two modes; first it tends to magnetize the sample, which increases the coil's inductance. Second, the alternating current magnetic field also induces eddy currents in the sample, which tend to oppose the driving current and reduce the coil's inductance [9]. At a low frequency, the eddy currents in the sample are very weak; the contribution to the inductance change is mainly from the magnetisation of the sample and therefore the real inductance measured is related to the sample permeability. As the frequency is increased, the effect of the eddy currents become more dominant.

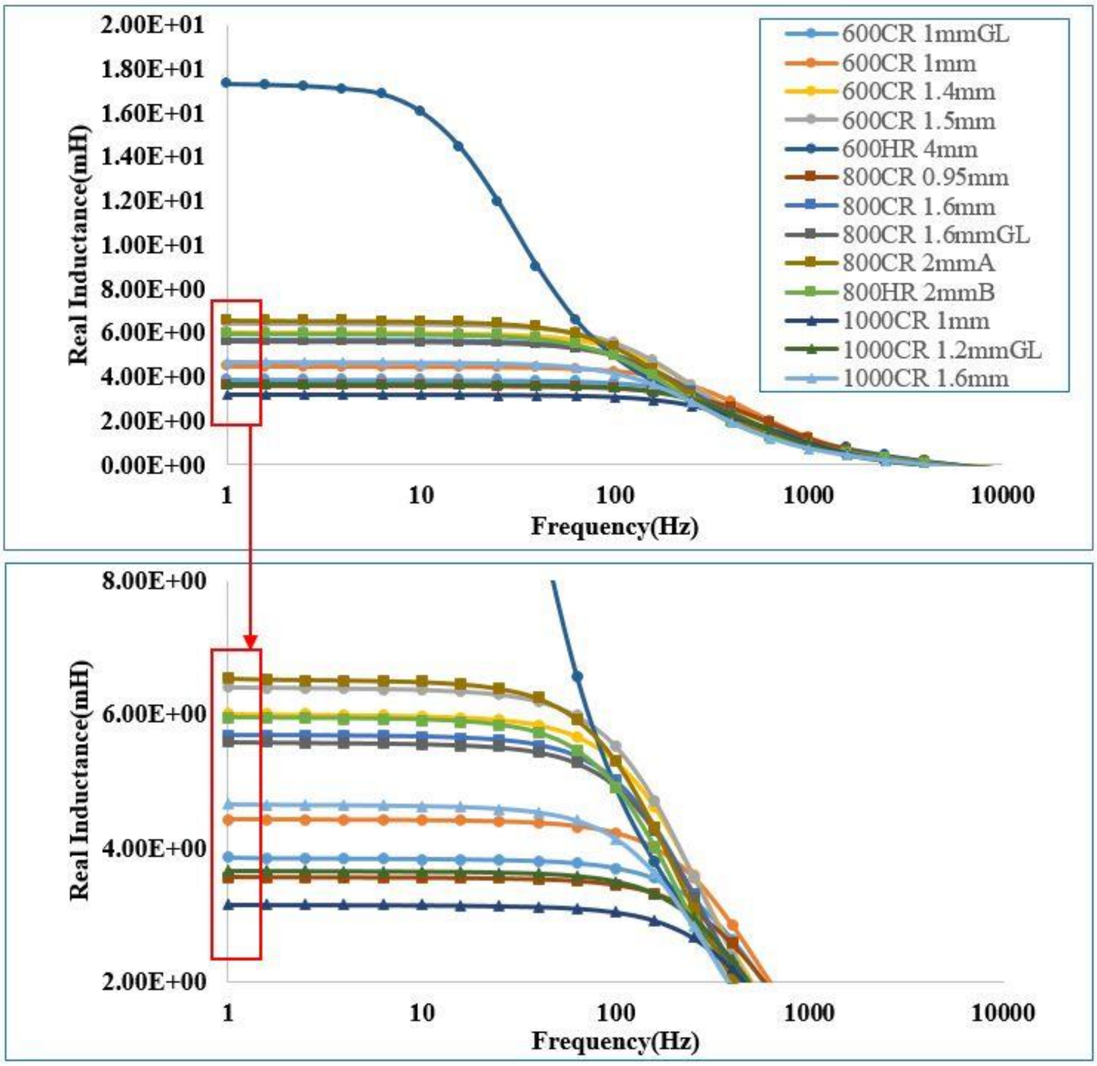

Fig 6. The real inductance versus frequency plot for the U-shaped EM sensor has a plateau in inductance value at low frequency (1-10Hz).

Therefore the real inductance versus frequency plot for the U-shaped EM sensor has a plateau in inductance value at low frequency (1-10Hz) in the region where the signal is independent of the electrical resistivity but dependent on the relative permeability of the sample. Therefore, the low field relative permeability value is determined from the experimental EM sensor measurement in that region.

It has been reported that the EM sensor signal of low frequency (10Hz) inductance increases almost linearly with ferrite fraction in the range of 35-73% for constant thickness (1.4mm) sample, which all have a similar grain size [15]. On the other hand, from Fig 7, it can be observed that for the commercial DP steel material with different thicknesses the inductance is strongly affected by the thickness of the sample.

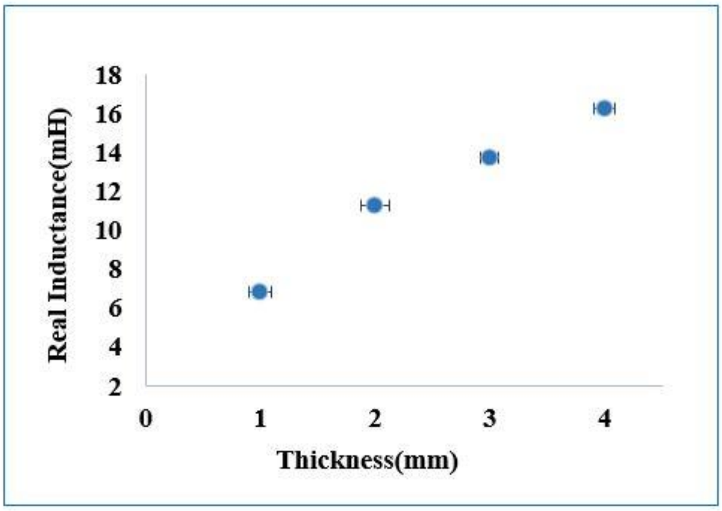

Fig 7. The real inductance measurements (using the U-shaped EM sensor at a frequency of 10Hz) for a commercial DP600 material (with 79% ferrite, average grain size 10 ±4μm) machined to thicknesses of 1mm - 4mm

The thickness of material affecting the sensor signal can be estimated by the skin depth (Δs) equation;

$$\Delta s = \sqrt{\frac{\rho}{\pi f \mu_0 \mu_r}} \qquad \text{Eq. (1)}$$

where ρ is the resistivity of the conductor, f is the frequency, μ is absolute magnetic permeability ($\mu = \mu_0.\mu_r$). By assuming that resistivity, $\rho = 2.1x10^{-7}$ Ω.m and permeability for DP steel is around 100 to 177, the value of skin depth for the current set up and operation frequency of 10 Hz, was estimated to be approximately 6 mm, which is larger than the sample thicknesses. Therefore, a thicker sample shows a higher mutual inductance sensor response as effectively more material is being measured. This means that the sensor signal cannot be correlated to tensile strength directly if different thickness samples are assessed unless a calibration curve to account for thickness is generated. Whilst this can be done experimentally it would require samples of different thickness for the different grades as the relationship between thickness and sensor signal for different permeability materials will not be linear. This is a time consuming and expensive process, and would need to be repeated if a different sensor were constructed. Therefore, a calibration curve to consider thickness, for different DP samples, was constructed using the 3D finite element model developed in COMSOL Multiphysics, Fig 1. Whilst the model does require a limited number of samples for validation once established it can also be used to consider sample geometry as well as thickness changes for different grades if required.

Fig 8 illustrates the calibration curves to obtain the permeability from the EM sensor mutual inductance value and measured sample thickness. The results from the model show good agreement with the experimental results. The results from Fig 5 show that there is a link between permeability and tensile strength, which indicates that measuring the permeability using an EM sensor on steel strip samples will allow the tensile strength to be predicted. In addition information about the ferrite fraction in the steel can be obtained from the permeability (from Fig 4) if the grain size remains similar (for example for steels produced with a similar hot rolling process). The calibration curve is required so that any DP sample thickness can be tested with the material permeability being determined, which can then be used to determine the strength. Using the calibration curve and the measured inductance from the EM sensor the permeability of the commercial DP samples can be determined hence the tensile strength can be predicted using Fig 5.

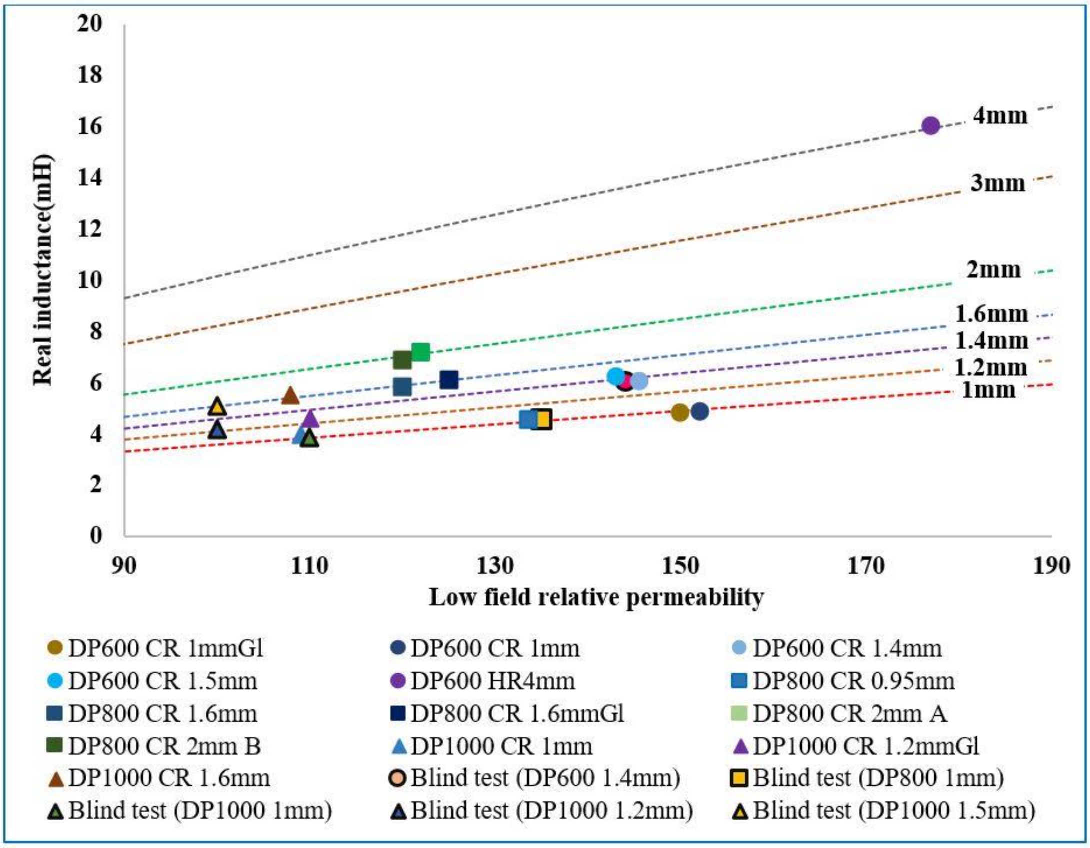

Fig 8. Calibration curves relating low frequency (10Hz) real inductance with permeability for different thickness samples. The dashed lines represent modelling results (for 1mm to 4mm strip thickness) and experimental data for commercial DP samples of different thicknesses are indicated by different points.

The permeability can then be used to estimate the tensile strength for DP steels. In order to evaluate the accuracy of the system (i.e. the EM sensor and the calibration curve), the tensile strength of five unknown DP steels with different thicknesses (blind test samples listed in Fig 8) were quantitatively predicted. The accuracy in prediction of tensile strength was 90%. Further work to improve the sensitivity of the system, particularly for the high strength DP steel, in term of sensor design and FE model accuracy is on-going.

4. Conclusions

Previously EM sensors have been shown to be sensitive to changes in ferrite fraction in DP steel sheet of constant thickness with little variance in grain size. In this paper it has been shown that the permeability can be determined from the low frequency mutual inductance measured using a U-shaped electromagnetic sensor for any sheet thickness using a calibration curve to account for the effect of thickness. The calibration curve was determined using a FE model for the sensor and sample geometry and verified with experimental results, this approach makes is quick and simple and removes the need for multiple calibration samples. The permeability is affected by the ferrite fraction and ferrite grain size for the DP steels, both of which affect the tensile strength, therefore a single relationship between permeability and tensile strength results allowing the tensile strength to be predicted from the EM sensor low frequency mutual inductance. In addition information on the microstructure can be inferred from the EM signal.

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