EM Sensor System for Characterisation of Advanced High Strength Strip Steels

Mohsen JOLFAEI\textsuperscript{a,1}, Jialong SHEN\textsuperscript{a}, Andrew SMITH\textsuperscript{b}, Lei ZHOU\textsuperscript{a}, Claire DAVIS\textsuperscript{a}

\textsuperscript{a}Warwick Manufacturing Group, University of Warwick, Coventry, CV4 7Al, UK
\textsuperscript{b}Tata Steel, University of Warwick Science Park, Coventry, CV4 7EZ, UK

Abstract. In order to obtain accurate quality control of steel products, it is desirable to be able to monitor the mechanical properties non-destructively. This study proposes using an electromagnetic (EM) sensor, suitable for use on strip samples, as a tool for non-destructive steel characterisation, in particular phase balance and grain size in dual phase (DP) steels and hence strength. It is known that the low frequency inductance measured using an EM sensor depends on the relative permeability of the sample and that the permeability is affected by microstructural features (i.e. phase fraction / distribution and, to a lesser extent, grain size are the important features in DP steel). EM sensors can be used to characterise austenite and ferrite fraction in hot strip mills (EMspec\textsuperscript{TM} system) and for statistical correlations to mechanical properties (IMPOC and HACOM systems) in cold strip mills. In this paper an EM sensor system and a finite element based sensor – microstructure model have been used to characterize DP microstructures (using commercial DP600, DP800 and DP1000 grades and a heat treated DP600 grade) taking into account the effect of strip thickness on the signals. This paper also reports on the relationship between the ferrite fraction and tensile strength, which follows the expected relationship from the literature, and the magnetic permeability (determined from the EM sensor signal which is directly related to ferrite fraction and grain size) and tensile strength. The ability of the EM sensor to determine the tensile strength is therefore illustrated taking into account strip thickness and microstructure.

Keywords. Electromagnetic sensor, permeability, mechanical property, DP steel

1. Introduction

The increasing requirements of passenger safety, vehicle performance and fuel efficiency 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 allowing light-weighting of automotive components. DP steels are characterised by a combination of continuous yielding behaviour, good formability and high tensile strength [1]. The microstructure of DP steels generally consists of a soft matrix of ferrite with typically 20-80\% dispersion of second phase (e.g. martensite, tempered martensite and/or bainite) [2]. The mechanical properties of DP steel are strongly influenced by its microstructural parameters, in particular phase balance and grain size [3-5].

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 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 permeability and resistivity of steel, with the low frequency inductance values being directly related to the permeability. The EM sensor measurements are non-destructive, have a fast response, can operate in a non-contact manner, are unaffected by dust, water and are relatively inexpensive [6]. In recent years, the use of magnetic techniques based on EM sensors, for non-destructive testing have increased [6-9]. 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 [10, 11]. Hence there is potential for using a U-shaped EM sensor to characterise the microstructure in DP steels, with verification previously shown for DP structures within the range of ferrite fraction from 35-72% using samples of constant thickness. As there are known relationships between the microstructure of DP steels with tensile strength [3-5,12], the EM signals can therefore be used to estimate 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 [13]. In that work only single sheet thickness DP steel samples were considered and a full sensor model, which could take into account sample geometry, was not available. This paper reports on the use of an EM sensor for 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.

2. Experimental Procedure

A number of commercial DP600, 800 and 1000 grade steels of different thicknesses (1 – 4 mm), supplied by Tata Steel Europe and a set of heat treated DP600 grade of 1.4 mm thickness (heat treated to generate different ferrite-martensite fractions from 35% to 72% ferrite) 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 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 required to avoid edge effects during testing (although this could be accounted for using the FE sensor model if required). The sensor consists of one excitation coil with 100 turns and two sensing coils with 86 turns 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 1260 with an AC voltage of 3V at a frequency of 10Hz and measurements of inductance in the sensing coil were taken for the specimens.

The samples for incremental permeability measurements (strip shape with 50mm length and 5mm width) were prepared by EDM wire cutting from the as-received DP steels. A BH measurement system, developed at the University of Manchester [14] and shown in Figure 1, was used to measure the permeability of the samples. A current with low frequency time varying signal was applied to the excitation coils wrapped around the silicon steel core. The strip samples were fitted into the slot in the core to maximise coupling between the core and the sample. The axial applied field (H) and the flux density of the induced field (B) were measured. A sinusoidal excitation of 10 Hz was used to generate minor loops (deviation from the initial magnetisation curve). The sample was firstly demagnetised then the applied field (H value) gradually increased and minor loop cycles recorded. The incremental permeability was calculated according to Eq. (1);

\[
\mu_{\Delta} = \frac{\Delta B}{\Delta H \mu_0}
\]  
Eq. (1)

where \(\mu_0\) is the permeability of free space.

**Figure 1.** The BH measurement system, developed at the University of Manchester, to measure BH hysteresis loops and permeability of strip sample.

3. Results and Discussion

3.1. Microstructure and mechanical properties

Typical SEM images of the DP600, DP800 and DP1000 steels are shown in Figure 2. As can be seen, the microstructure of dual phase steels consists of a ferrite matrix containing a second phase in the form of islands (martensite, bainite and/or tempered martensite) [15]. Different volume fractions of ferrite and martensite / bainite are present in the different grades of DP steels, used to give the different strength levels [3,4,15].
Figure 2. SEM images of commercial DP600, DP800 and DP1000 steels. The microstructures consist of a ferrite matrix (black) containing a second phase in the form of islands (martensite, bainite and/or tempered martensite).

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 the DP steel is well known and widely documented [2,4,5,16]. This is in agreement with the results shown in Figure 3. There is a clear decrease in the tensile strength with an increase in ferrite fraction for DP grades, which is related to the lower martensite (or bainite) fraction.

The trend follows an approximately linear relationship for the DP samples ($R^2 = 0.86$). This trend stems mostly from the composite effect due to the presence of hard particles in a soft matrix. From Figure 3 it can be seen that there is a lot more scatter for the DP800 grades. To determine the cause of the scatter, a 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 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 the effect of ferrite grain size variation will be less significant on strength as the ferrite fraction is low (approximately 40%).

In term of mechanical properties, grain boundaries may act as obstacles to dislocation slip. At room temperature, yield stress $\sigma_y$ depends on the inverse square root of the grain size, i.e. the Hall–Petch relationship [15-19] and grain size affects tensile strength [20]. 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 [21-23]. Therefore it might be expected that not only ferrite fraction but also ferrite grain size will affect the magnetic properties in DP steels. The results in Figure 4 show a strong effect of ferrite fraction on the low field permeability, as has been seen previously [24]. In addition, 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.
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 incremental permeability (determined from the BH hysteresis loops) is plotted against tensile strength in Figure 5. The results indicate that there is a general correlation between permeability and tensile strength for the commercial DP steels. 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 effect of decreased dislocation density (from martensite formation), easier reverse domain formation and domain wall motions take place at a lower applied field in ferrite [23]. The correlation in Figure 5 is not linear but there is less scatter around a line of best fit than in Figure 4.

3.2. EM sensor measurements and FE Modelling

The real inductance versus frequency plot for the U-shaped EM sensor shows a plateau in inductance value at low frequency (10-100Hz) in the region where the signal is independent of the electrical resistivity but dependent on the relative permeability of the sample. It can be seen in Figure 6 that the EM sensor signal of low frequency inductance increases almost linearly with ferrite fraction in the range of 35-73% for the uniform
thickness (1.4mm) heat treated DP600 steels, which all have a similar grain size. On the other hand, from Figure 7, it can be observed that for the commercial DP steel grades with different thicknesses (and similar ferrite fraction) the inductance is strongly affected by the thickness of the sample.

The thickness of material affecting the sensor signal can be estimated by the skin depth equation, Eq.(2);

\[ \Delta s = \frac{\rho}{\pi f \mu_0 \mu_r} \]  

Eq. (2)

where \( \rho \) is the resistivity of the conductor, \( f \) is the frequency, \( \mu \) is absolute magnetic permeability (\( \mu = \mu_0 \mu_r \)). By assuming that resistivity, \( \rho = 2.1 \times 10^{-7} \Omega \cdot m \) and permeability for DP steel is around 100 to 170, the value of skin depth for the current set up and operation frequency of 10 Hz, was calculated to be approximately 6mm, which is larger than the sample thickness. 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.

A calibration curve to consider thickness, for different DP samples, was constructed using a 3D finite element model developed in COMSOL Multiphysics, Figure 8.

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**Figure 6.** The real inductance measurements (using U shaped EM sensor) of heat treated DP600 steel at a frequency of 10Hz versus ferrite fraction.

**Figure 7.** The real inductance measurements (using U shaped EM sensor at a frequency of 10Hz) of DP600 samples (with 79% ferrite, grain size 10 \( \pm \) 4μm) steels.

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**Figure 8.** U-shaped EM sensor on the strip sample (a) and 3D U-shaped FE model to estimate the permeability of specimens (b).
The 3D sensor model was constructed based on the measured geometry of the sensor and number of windings for the excitation and sensing coils. The model was validated using measured signals for samples of known permeability (determined using the BH system) and thickness. It is important to note that the low field permeability value is required as the EM sensors used in this work apply a field in the range of 500A/m and the measured value of permeability is a function of magnetic field.

Figure 9 illustrates the calibration curves to obtain the permeability from the EM sensor mutual inductance value and measured sample thickness. Both model generated curves and validation points from the DP steels used in this work are shown. Good agreement between the model and measured values can be seen. The results from Figure 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 (Figure 4) if the grain size remains similar.

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 accurately predicted using Figure 5.

![Figure 9. Calibration curves relating low frequency (10Hz) real inductance with permeability for different thickness samples. The lines represent modelling results and experimental data for samples are indicated by different points.](image)

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 is 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. The permeability is affected by ferrite fraction and ferrite grain size for DP steels, both of which affect the tensile strength, therefore a single relationship between permeability and tensile strength results. The permeability can then be used to estimate the tensile strength for DP steels.
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References