NDT&E International 67 (2014) 31–35

Contents lists available at ScienceDirect

NDT&E International

journal homepage: www.elsevier.com/locate/ndteint

Quantification of the phase fraction in steel using an electromagnetic sensor

L. Zhou [a,*], J. Liu [a], X.J. Hao [a], M. Strangwood [a], A.J. Peyton [b], C.L. Davis [a]

[a] School of Metallurgy of Materials, University of Birmingham, Edgbaston, Birmingham, UK
[b] School of Electrical and Electronic Engineering, University of Manchester, Manchester, UK

ARTICLE INFO

Article history:
Received 4 January 2014
Received in revised form
23 June 2014
Accepted 27 June 2014
Available online 11 July 2014

Keywords:
Relative permeability
Magnetic sensors
Dual phase steels
Ferromagnetic materials
Finite element analysis

ABSTRACT

The effect of ferrite fraction, in 0.17–0.8 wt% C steels with ferrite–pearlite microstructures, on multi-frequency electromagnetic (EM) sensor readings has been studied. The measured initial relative permeability values agreed well with finite element microstructure model predictions. The EM sensor low frequency inductance value is sensitive to changes in relative permeability and the sensor can measure ferrite fraction in dual-phase steels. Therefore, EM sensors could be used to assess dual-phase (ferrite + pearlite/bainite/martensite) steel microstructures in a non-contact, non-destructive manner.

1. Introduction

Strip steels with dual or multi-phase structures are widely used in the automotive industry. The microstructure of dual phase steels often consists of a matrix of ferrite, with typically 20% dispersion of second phase (e.g. martensite or bainite) islands [1]. The microstructure is produced either by controlling the transformation of austenite after hot rolling or by intercritical annealing after cold rolling [2]. The amount and type of any second phase play an important role in determining mechanical properties. In order to obtain accurate quality control, it is important to be able to monitor the phase fraction non-destructively. Several techniques could be employed such as X-ray, electromagnetic or ultrasonic sensors [3–6]; 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.

EM sensors exploit the difference in magnetic properties, such as relative permeability, and electrical conductivity between samples with different microstructural phase balances. In ferromagnetic steels, the change in relative permeability has a significant effect. Previously, multi-frequency EM sensors have been shown to be able to measure austenite/ferrite fraction from 0% to 100% in model (HIPped austenitic/ferritc stainless steel powder) alloys [7,8]. The large difference in magnetic properties of ferrite (ferromagnetic) and austenite (paramagnetic) phases makes the change in signal large and hence relatively easy to measure. EM sensors have also measured the levels of decarburisation (variation in ferrite content with depth) in steel rod [9,10]. The approach adopted to relate the overall steel EM sensor signal to its microstructure has been to construct a finite element (FE) model for the microstructure (phase, region size and distribution). The EM properties of the individual phases are assigned to those regions to give the overall EM properties of the steel. Within the model the particular sensor geometry is included (e.g. two-dimensional axisymmetric for a cylindrical sample and tubular sensor [10]) and the interaction with the steel and any external circuits predicted. In this way different microstructures and sensor designs can be compared.

When considering the effective electrical or magnetic property of a material which has two components with contrasting properties, power law models have been popularly used [8,11–13]. The power law model predicts the effective permeability as

$$\mu_e^{\beta} = (1-f)\mu_1^{\beta} + f\mu_2^{\beta} \tag{1}$$

where μ_1 and μ_2 are the relative permeability values of the first and second phase respectively, f is the fraction of the second phase, and β is a dimensionless parameter. Examples of the power law are the Birchak formula ($\beta = 1/2$) [13] and the Looyenga formula ($\beta = 1/3$) [12] 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 model was found to give good agreement with measured

* Corresponding author. Tel.: +44 121 4145174; fax: +44 121 4147468.
E-mail address: l.zhou@bham.ac.uk (L. Zhou).

http://dx.doi.org/10.1016/j.ndteint.2014.06.007
0963-8695/

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 β value to give good fitting) [8]. Large changes in EM signal have been reported for ferrite–austenite microstructures as austenite is paramagnetic and ferrite is ferromagnetic, however, the majority of multi-phase steel microstructures contain a mix of ferromagnetic phases (i.e. ferrite, pearlite, bainite and martensite). Whilst EM sensors have been employed on-line for measuring phase balance during transformation after steel hot rolling, i.e. microstructures of ferrite and austenite [14], research is needed to determine if an EM sensor can quantify the phase balance in steel microstructures comprised of different ferromagnetic phases. In this paper, the initial relative permeability values of ferrite/pearlite microstructures with different ferrite fractions were determined by a fitting the EM sensor readings with the FEM model. The results have been compared to power law models and FEM microstructure modelling results.

2. Materials and methods

Melting grade (pure) iron and hot rolled C–Mn steels with different carbon contents have been tested with an EM sensor. The chemical compositions of the steels used are given in Table 1.

Metallographic samples were taken in the transverse direction of the steels, polished to an OPS finish and etched in 2% nital. The samples were imaged using a Zeiss Akioskop-2 optical microscope equipped with Axiovision 4.6.3 image capture software. The ferrite fraction and ferrite grain size of the samples were analysed using “Image J” image analysis software. The hardness was measured on polished samples by Vickers micro-hardness measurement with a 500 g load.

Samples for laboratory EM measurements (cylindrical shape with 4.95 mm diameter and 50 mm length) were machined from the as-received steel. The EM sensor, which is similar to that used in [10], has exciting and sensing coils that are air-cored. Each coil has an inner diameter of 7.95 mm, 0.2 mm height, 10.5 mm length and 56 turns. The coils were driven by a frequency response analyser (SL1250) from 10 Hz to 65,000 Hz, and the real inductance values were determined from mutual inductance measurements. It should be mentioned that the lab based axial sensor with machined cylindrical samples was used in this study for the relative permeability modelling. The principle of the sensor is the same to a detector type (H shape/U shape) EM sensor, which can be applied for industrial use. Electrical resistivity measurements were performed at room temperature using a conventional four point DC method with a Cropico DO5000 microohmmeter. Each resistivity value was determined by taking the average of 10 measurements on the same sample used for EM sensor measurements. The experimental measured EM sensor output together with the resistivity value were used with a two-dimensional COMSOL FE model developed for the sensor-sample geometry, and the relative permeability was predicted by fitting the modelled results to the experimentally measured ones. The geometry setup of the sensor and sample in the model is shown in Fig. 1. The exterior boundaries were set as magnetic insulation and the interior boundaries were set as continuity. Extra fine physics controlled mesh (defined by COMSOL software) was applied to the entire geometry with refined mesh to the sample geometry. The complete mesh of the model consists of 14,782 domain elements and 758 boundary elements. Computation time for each fitting is about 15 min using a quad core (i7) processor with 16G RAM. The details of the fitting method is described in [15].

Table 1
Chemical composition for the steel samples used in this work, all in wt%.

	C	Si	Mn	S	P	Cu
0.17C	0.17	0.28	0.80	0.03	0.01	0.09
0.38C	0.38	0.26	0.75	0.03	0.02	0.12
0.53C	0.53	0.29	0.72	0.01	0.02	0.09
0.80C	0.80	0.20	0.96	0.03	0.02	0.02

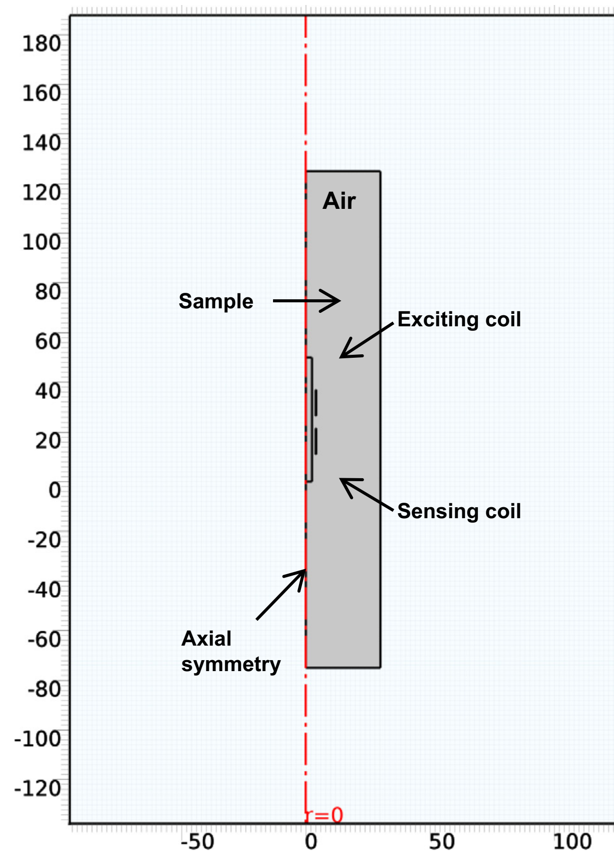

Fig. 1. Geometry setup of the sensor and sample in the FE sensor output model.

3. Results and discussion

Optical microstructures of the pure iron, 0.17C, 0.38C, 0.53C and 0.8C as-received samples using a 40× objective are shown in Fig. 2. Table 2 shows a summary of the average ferrite grain size (ECD), ferrite percentage, hardness and resistivity with standard deviation values. The resistivity value increases with carbon content due to the different amounts of pearlite formed.

The measured real inductance versus frequency (logarithmic scale) results for the as-received pure iron, 0.16C, 0.53C and 0.8C steel samples, using the EM sensor are shown in Fig. 3. The EM field produced by the exciting coil in the sensor acts on the steel samples in two ways [10]. At lower frequencies, it tends to magnetise the sample thus an inductance value occurs. Here, the relative permeability of the sample dominates the inductance value. Secondly, the change in magnetic field induces eddy currents that oppose the driving current and the inductance decreases. As the frequency increases, eddy currents become more important so that the real inductance begins to decrease and eventually the EM signal approaches a very low inductance value, where the samples cannot be easily distinguished. The low frequencies (below approximately 100 Hz) real inductance values