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Modeling and experimental study of a multi-frequency electromagnetic sensor system for rail decarburisation measurement

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ABSTRACT

This paper presents a modeling and experimental study using a multi-frequency electromagnetic (EM) sensor system, for non-destructive evaluation of rail decarburisation. The EM sensor is configured with a H-shaped ferrite core, which was excited with a multi-frequency waveform over the range of approximately 1–100 kHz. Finite-element (FE) simulation was carried out to establish the link between the EM sensor output and the level of decarburization. Rail samples with different levels of decarburisation, due to different bloom reheat times prior to rolling were tested in the laboratory. It was found that the zero-crossing frequency of the EM sensor response is linearly proportional to the decarburisation level by FE simulation, theoretic analysis and experiment. This finding is helpful in understanding the response of the EM sensor to rail decarburisation and could lead to a non-contact, non destructive method for use during rail manufacturing. In addition, on-site measurement (tests carried out in the Rail & Section Mill at Tata Steel) was taken on a 110 m long rail product, with the results indicating that the EM sensor response correctly follows the expected decarburisation profile along the rail length.

1. Introduction

Reheating of steel prior to hot rolling is normally conducted in an air atmosphere with the temperature as high as 1250 °C. At such high temperatures, carbon atoms at the surface of the steel can be removed by reacting with oxygen in the surrounding atmosphere; this process is known as decarburisation. The speed of losing carbon at the surface is more rapid than replenishment by solid-state diffusion; over a period of time a partial or continuous decarburised surface layer is formed [1–4]. As hardness, fatigue resistance and wear properties are strongly dependent on carbon content; the loss of carbon at the surface of the steel can have a significant negative effect on the mechanical properties of steel products [5–7]. In the case of rail, decarburisation has potential wear implications and a maximum allowed decaburisation depth is specified in the standards, therefore it requires accurate measurement.

At present, decarburisation is measured using destructive methods, such as metallographic observation or hardness tests on a rail cross section. Both of these methods are destructive, time consuming and cannot be used for on-line processing. Recently, the possibility of using non-destructive methods to determine decarburisation depth, such as magnetic Barkhausen noise (MBN) emission [8] and eddy current, has been investigated [9–14]. This paper reports on the development on a multi-frequency eddy current method for rail inspection.

Previously, we have found that the zero-crossing frequency of the H-shaped electromagnetic (EM) sensor output is linearly proportional to the magnetic permeability of steel [15], which gives the possibility of using this EM sensor to measure decarburisation, by the differences in the magnetic permeability between decarburised ferrite and the normal rail steel microstructure of pearlite. We have reported the evaluation of decarburisation thickness for heat treated cylindrical samples using an air-cored eddy current sensor [16], however, for rail samples, due to its different geometry this air-cored sensor is not suitable as it relied on a circular coil to enclose the sample. The H sensor considered in this paper can be deployed close to, but not touching or interfering with, the rail surface, and used to monitor continuous lengths of rail. This is the first time the use of the zero-crossing frequency response from an H-shaped EM sensor to estimate the decarburisation depth for rail samples has been reported. In addition, this is the first report of the use of an EM decarburisation measuring system in an industrial environment demonstrating that the technique can be transferred from laboratory.

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2. Method

The electromagnetic field created by the excitation coil of an EM sensor placed near the surface of rail is sensitive to the distribution of the magnetic permeability and electrical resistivity within the rail. The effect of the rail is manifest as a variation of the trans-impedance between the windings in the sensor. Both magnetic permeability and electrical resistivity are affected by any change in the microstructure due to the formation of a decarburisation layer. In general, decarburisation causes the steel to soften magnetically resulting in a significant increase in differential permeability and a relatively smaller decrease in electrical resistivity [16,17].

The response of an H-shaped sensor to the electromagnetic properties of steel plate/strip has been previously studied for a sensor for measuring transformed fraction (austenite to ferrite transformation) on the run-out table of a hot strip mill [15]. Where there is an air gap between the sensor and the test piece, the zero-crossing frequency can be described as:

$$\omega_0=\frac{\mu_r\alpha_0^2}{\mu_0\sigma} \tag{1}$$

where μ_r is the magnetic permeability and σ is the electrical conductivity and α_0^2 is a constant, which is related to the sensor geometry. Eq. (1) shows that the zero-crossing frequency is linearly proportional to the magnetic permeability of the steel sample. The link between steel microstructure (decarburised ferrite), EM property (magnetic permeability), and hence to the sensor output (zero-crossing) shows the potential of using the multi-frequency EM method in decarburisation evaluation.

3. Three-dimensional (3-D) finite element analysis

The commercial EM solver (ANSYS MAXWELL) was employed for the finite element (FE) simulation. The 3D model is shown as Fig. 1.

Fig. 1(a) shows the model geometry in general. The sensor has five coils, one excitation coil and four flux-sensing coils as shown in Fig. 1(b). The two upper sensing coils are used for reference and the two lower sensor coils are used to detect the change due to the rail samples. This kind of H-shaped design can be thought of as two U cores joined back to back with a common excitation coil. Adjacent pairs of secondary pickup coils are wired in series, therefore maximizing the signal of interest while helping to reduce the common mode interference caused by an ambient magnetic field. The H-shaped ferrite core is 23 mm high and 15 mm wide. The separation between the poles of the sensor is 5 mm and the pole cross section is 4 mm by 6 mm. The relative permeability of the ferrite core, as specified by the manufacturers, is 1000 and the conductivity is 0.01 S/m. The steel sample in the model is divided into six layers with 0.19 mm, 0.05 mm, 0.02 mm, 0.13 mm, 0.31 mm and 1 mm thickness from the top to the bottom), shown in Fig. 1(b), to represent the different decarburisation depths observed on the rail samples used for experimental measurements (discussed below). The values of relative permeability of 50 and 200 were used to present pearlite and ferrite respectively [16] and the decarburized layer was modeled as a fully ferritic layer. The decarburization layer in rail is not fully ferritic, although part of the layer may be fully ferritic, which means the relative permeability value will be lower than 200, however based on previous work [16] it has been found that using ferrite to model the decarburization layer give acceptable results. In the initial model the top 0.19 mm layer was set as 200 and the other five layers as 50 to stand for the rail sample with 0.19 mm thick full decarburisation layer. The distance (lift-off) between the sensor and the rail was 3 mm. Later deeper decarburisation layer samples were represented by setting the other layers' permeability as 200 in sequence. The conductivity of the sample was set as $1.\ 1\times10^6$ S/m.

The five curves in Fig. 2 show the change in mutual inductance between the central excitation coil and the differential connected receiver coils caused by the presence of the rail. The induced magnetic field in the target acts in two ways: at lower frequency, it tends to magnetise the target, which leads to the increase in inductance, and with increasing frequency, the eddy current effect becomes dominant and tends to reduce the inductance. At the zero-crossing frequency the two effects are balanced and inductance goes to zero. The curves represent the situations for samples with 0.19 mm, 0.24 mm, 0.26 mm, 0.39 mm and 0.70 mm continuous full decarburisation layers (i.e. fully ferrite). Our previous paper [18] has shown that the decarburisation depth has a linear relationship with inductance at 1 kHz, which is also shown in Fig. 2, where the inductance increases with the decarburisation depth increase from the bottom curve to the top at low frequencies. However, in [19] the zero-crossing frequency has been found to be more independent to lift-off compared with inductance at low frequency, thus in this paper the linkage between zero-crossing frequency and rail decarburisation level has been investigated. The zero-crossing frequency can be seen to increase with the increase of the decarburisation layer from left to right, except the 0.24 mm decarburisation sample and 0.26 mm decarburisation sample due to their very similar decarburisation levels.

Fig. 3 illustrates the relationship between zero-crossing frequency and decarburisation thickness, which suggests that decarburisation depth, has an approximately linear relationship with zero-crossing frequency values predicted by the FE EM models.

4. Experimental setup and result analysis

Five commercial rail samples with different re-heat furnace dwell times prior to hot rolling, supplied by Tata Steel Scunthorpe Rail & Section Mill, were used to test the response of the EM sensor to decarburisation in the lab. The average decarburisation depths across the crown position of the rail head were measured from optical micrographs by Tata Steel. Average decarburisation depths of the samples are provided in Table 1.

The H-shaped sensor was mounted in a plastic housing and encapsulated with epoxy resin. The sensor was connected to a multi-frequency data acquisition unit, which was developed in partnership with Primetals Technology. A notebook PC was used to record the impedance spectra. A plastic spacer defined the lift-off between the sensor and rail as shown in Fig. 4.

The excitation coil had 60 turns and the sensor coils also had 60 turns. The geometry of the sensor is the same as in the 3D FE model. The lift-off effect was investigated by testing the sensor at a fixed position on the rail for different lift-offs.

Fig. 5 shows that the zero-crossing frequency reduces with an increase in the lift-off, thus the lift-off needs to be determined during the measurements. The error bars indicate the degree of scatter in zero-crossing frequency measurement for the same position at each rail sample over the seven readings taken. Fig. 6 shows the measured relationship between inductance changes versus lift-off for the same three decarburisation levels at 1 kHz. At 1 kHz, for ferritic steel (μ_r of 200 and σ of 1.1x10^6 S/m) the skin depth is around 1 mm, which is suitable compared with the decarburisation layers of available samples. Lift-off clearly effects both crossover frequency and amplitude, however with lift-off changes from 0.5–5 mm, zero-crossing frequency drops to 1/3 and inductance decreases to 1/10, which indicates that zero-crossing frequency is more independent compared with inductance. Therefore lift-off must either be fixed using appropriate mechanical means or compensated for electronically using the amplitude of the received signal response. The following measurements were carried out with the lift-off fixed at 3 mm and the signal could clearly distinguish the samples with different decarburisation depth. Fig. 7 shows the recorded zero-crossing frequencies and estimated decarburisation depth at different positions in the central crown area for each rail sample.