Estimation of Decarburization Depth by Magnetic NDE Technique

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Abstract

The carbon loss has a large effect on hardness, strength, wear resistance and fatigue properties in many steels like rail steel, spring steel etc. Therefore, the extent of decarburization has a prime importance in many engineering components based on these steels. The aim of present investigation is to analyze decarburization depth of rail steel (Fe-0.65C-0.23Si-1.17Mn-0.02P-0.02S) through an electromagnetic NDE sensor, named as MagStar, which is developed in CSIR-NML. The decarburized steel sample is prepared after heat treatment at temperatures of 1000°C for 5, 16 and 50h followed by air cooling. In as-received condition, rail steel comprises a fully pearlitic microstructure. During high temperature processing, carbon percentage of steel continuously decreases from core to surface due to decarburization, resulting in conversion of pearlitic to ferritic microstructures. Since ferrite is magnetically softer phase than pearlite, coercivity of decarburized steel continuously decreases with increase in thickness of ferrite layer. Therefore, the developed electromagnetic sensing device MagStar can be implemented for analyzing decarburization during processing of high carbon steel.

Keywords: Annealing, rail steel, decarburization, coercivity, Barkhausen emission, ferrite.

1. Introduction

To control microstructure and mechanical properties, steels are occasionally heat treated and processed at the austenitic phase region of 800-1200°C temperature ranges. These high temperature operation results in the loss of carbon content through decarburization technique. The carbon loss has a large effect on many carbon affected properties like hardness, strength, wear resistance and fatigue properties, which in turn deteriorate the performance of many steels such as rail steel, spring steel etc. Therefore, the measurement of depth and degree of decarburization has a prime importance in many engineering components based on these steels. The decarburization depth is mainly measured through destructive or semi-destructive techniques such as microscopy, hardness and spectrographic analysis, which correspond to measurement of ferrite fraction by quantitative microscopy, degradation of hardness along cross section and carbon analysis at decarburized surface layer, respectively. Therefore, these techniques are not only time consuming but also improper for application of measuring instrument in remote and critical accessible places. In contrast, many non-destructive evaluation (NDE) methods, like magnetic Barkhausen emission (MBE) [1], eddy currents [2], are being applied for determination of decarburization in steels. The ferrite formation due to decarburization is estimated through the MBE profile height and position and the Fourier analysis of eddy current signal. Hao et al. has shown a close relation between the inductance and decarburization depth at varying decarburizing treatment time [3]. They have explained a multifrequency electromagnetic (EM) sensor in which low frequency inductance is suitable for 0% to 40% ferrite and zero crossing frequency is effective for 40% to 100% ferrite. Therefore, the selection of appropriate test frequency is important for estimation of decarburization depth through aforementioned EM sensor. Since ferrite is magnetically softer than pearlite, the measurement of magnetic hysteresis loop (MHL) parameters such as coercivity, magnetic flux density, may be also effective for decarburization estimation. The present authors have developed an electromagnetic NDE sensor,
named as MagStar, which can measure both MHL and MBE parameters and effectively explain the microstructural changes in heat treated steels [4, 5]. The aim of present investigation is to analyze decarburization depth of rail steel by MHL and MBE parameters using MagStar.

2. Materials and methodology

The rail steel of nominal composition (Fe-0.65C-0.23Si-1.17Mn-0.02P-0.02S) was chosen with the size of 70×30×15 mm³ for the decarburization treatment. The samples were annealed at 1000°C for 2, 16 and 50 h under normal atmosphere and followed by air cooling. Due to long time holding at austenitizing temperature (1000°C), the surface carbon was oxidized and the decarburized layer was progressed from surface to core. Fig. 1 shows the images of as-received and annealed samples. The as-received (Fig.1a), and the annealed samples of before (Fig.1c) and post acid (Fig.1d) rinsing were examined for magnetic property measurement and microscopy. A thick oxide layer was stuck at outer sample surface (Fig. 1b), which was readily removed by gentle tapping. The decarburized sample is further rinsed through a 20% dilute aqua regia acid solution. The magnetic properties were determined through MHL and MBE parameters using the electromagnetic sensing device MagStar with the applied field of 1500Oe and 1000Oe and the frequency of 50 mHz and 40 Hz, respectively [4]. The transverse section of each decarburized sample was mounted, polished and etched by 1% Nital solution for studying microstructures through an optical microscope of Leica DH2550.

![Fig. 1 Photographic images of rail steel samples](image-url)
3. Results and discussions

3.1 Microstructures of as received and annealed samples

As received rail steel comprises completely pearlite microstructure. Upon annealing at 1000°C for 50h under open atmosphere, the decarburization takes place on the steel surface, which effectively causes a ferrite layer on the surface (Fig. 2a). The degradation of microstructure consists of three different layers, viz., pearlite (core), ferrite-pearlite combined structure, and ferrite. A thin iron oxide layer is observed at the most outer surface, which is removed by acid rinsing treatment. The core (layer A) is mostly pearlite structure with a thin ferrite layer at the grain boundary (Fig. 2b). Due to long time (50h) holding at 1000°C, some ferrite layer formation takes place at grain boundary. The layer B comprises mixed microstructure of ferrite and pearlite owing to partial decarburization (Fig. 2c). The C is about 340µm thickness ferrite layer near to surface (Fig. 2d).

Fig. 2 Optical microstructures of decarburized rail steel sample annealed at 1000°C for 50h (a) transverse section and higher magnification of different layers (b) A (c) B and (d) C.

3.2 Magnetic properties of as-received samples

The pearlite is moderately hard magnetic structure compared to ferrite. It is clearly described through magnetic hysteresis loop (MHL) and magnetic Barkhausen emission (MBE) of low carbon steel of 100% ferrite structure and as-received rail steel, as shown in Fig.3. From MHL, the low C steel defines coercivity ($H_c$) of 54.6 Oe and magnetic flux density ($B_s$) of 18.13 kG, whereas the rail steel represents $H_c$ of 76.7 Oe and $B_s$ of 17.86 kG, confirming softer magnetic nature of low C steel than that of rail steel (Table 1). The soft magnetic phase ferrite also causes
easy magnetic domain movement, resulting in the low MBE voltages (rms and peak) compared to rail steel. Accordingly, the MBE peak shifting of rail steel takes place to the right side. After decarburization, the rail steel comprises the degradation of microstructure from outer surface to inner core region. The different microstructure layers largely affect the magnetic behavior of steel, which would be applicable for the estimation of decarburization.

![Magnetic Properties](image_url)

Fig. 3 Comparison of magnetic properties of low carbon steel and as-received rail steel samples by the curves of (a) magnetic hysteresis loop (MHL) (b) magnetic Barkhausen emission (MBE).

### Table 1: Magnetic parameters of low C-steel, rail steel (as-received and annealed) samples

<table>
<thead>
<tr>
<th>Samples (Processing condition)</th>
<th>Microstructural Phase</th>
<th>MHL parameters</th>
<th>MBE parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Coercivity (Hc) (Oe)</td>
<td>Magnetic flux density (Bs) (kG)</td>
</tr>
<tr>
<td>Low C Steel</td>
<td>Ferrite</td>
<td>54.6</td>
<td>18.13</td>
</tr>
<tr>
<td>Rail steel (as received)</td>
<td>Pearlite</td>
<td>76.7</td>
<td>17.86</td>
</tr>
<tr>
<td>Rail steel (Ann. 1000°C/50h)- Before acid rinsing</td>
<td>Iron oxide, ferrite and pearlite</td>
<td>85.08</td>
<td>7.05</td>
</tr>
<tr>
<td>Rail steel (Ann. 1000°C/50h)- Post acid rinsing</td>
<td>Ferrite and pearlite</td>
<td>57.44</td>
<td>16.33</td>
</tr>
</tbody>
</table>

### 3.3 Magnetic properties of decarburized samples

The sample immediately after annealing contains with a thick loosely oxide layer, which can be removed by gentle tapping. Some oxide is still adhered the sample, as shown in Fig. 1c, affect the magnetic behavior of sample. Due to paramagnetic nature, oxide scale decreases ferromagnetic nature of decarburized samples, resulting in an increase of coercivity and the decrease of magnetic flux density (Table 1 and Fig. 4a). Therefore, the acid rinsing is essentially needed prior to the determination of decarburization depth. Oxide layer also decreases MBE voltage of decarburized steel.
3.4 Correlation between decarburization depth and coercivity

To correlate decarburization depth with soft magnetic properties, three samples decarburized at 1000°C for 5, 16 and 50h have been found the ferrite layer formation up to the depth of 125, 265 and 340µm, respectively. The samples have a decreasing trend of coercivity with increasing decarburizing time. Consequently, a linear relationship is found between decarburization depth and coercivity (Fig.5). It confirms that coercivity is a potential magnetic parameter for the estimation of decarburization depth of steel during processing and service. Although this experiment is done at single decarburization temperature (1000°C), the elaborate experimentation at other temperatures is needed in future.
4. **Conclusions**

The following conclusions may be drawn from this investigation.

i) The magnetic parameters of decarburized rail steel can make a clear indication on the formation of surface oxide layer.

ii) The coercivity explains a good relation with the decarburization depth of rail steel treated at 1000°C for 5, 16 and 50h.

iii) The magnetic sensing device (MagStar) is a handy tool for the estimation of decarburization depth of steel during industrial processing as well as service condition.

**References**