The Structural health condition monitoring of rail steel using acoustic emission techniques

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Abstract

This paper discusses the work towards the development of a sound methodology for the application of acoustic emission techniques for detecting and monitoring crack growth in rail steels. At the moment rails that are found to be damaged on the network are not immediately replaced. Instead a speed restriction is imposed and affected rails are clamped with special fish-plates until they are replaced, usually after a period of a few days. Unfortunately damaged rails prior to their replacement cannot be reliably assessed for further crack growth with any of the conventional non-destructive evaluation techniques (e.g. ultrasonic) and this is the reason that a speed restriction is imposed. Acoustic emission techniques could potentially be applied for the detection as well as continuous monitoring of further crack growth therefore removing the need of imposing strict speed restrictions which can be as low as 20MPH (32km/h). In order to validate the potential of the AE technique tests are carried out under laboratory conditions on three and four-point bending samples. Various signal processing methods will be examined using AEWin and Noesis software supplied by PAC and Envirocoustics respectively.

Keywords: Acoustic Emission, Rail Steel, Crack Growth Monitoring

1. Introduction

Rail transport has been gaining pace over the past few decades throughout Europe as well as the rest of the world (particularly in China and the U.S.). Further investments are expected to continue until at least 2020 although the current pace is very likely to be maintained until 2030 (Europe Commission, 2011). Despite the current economic climate rail transport in terms of passenger number and freight tonnage has been growing. In the UK, the British rail network is getting busier and rail freight is exhibiting strong growth (International Union of Railways (UIC), 2011). Increasing fuel prices and climate change are likely to contribute further to the growth of British rail transport in the forthcoming years. A number of high-speed lines are currently being planned with the most prominent project in this area currently being the connection between Birmingham and London. Inspection and damage control of rails will be critical in ensuring the smooth operation of the British rail network in the forthcoming years (Papaelias, 2011).

This project is concerned with the development of a sound methodology for the application of acoustic emission techniques for detecting and monitoring crack growth in rail steels. At the moment rails that are found to be damaged on the network are not
immediately replaced. Instead a speed restriction is imposed and affected rails are replaced within a few days time. Unfortunately damaged rails cannot be reliably assessed for further crack growth with any other non-destructive evaluation techniques and this is the reason that a speed restriction is imposed. Acoustic emission (AE) techniques could potentially be applied for the detection as well as continuous monitoring of further crack growth therefore removing the need of imposing strict speed restrictions which can be as low as 20MPH (32km/h). The principle of AE technique is shown in Figure 1. In order to validate the potential of the AE technique tests are carried out under laboratory conditions on three and four-point bending samples. Various signal processing methods have been examined using Noesis software supplied by Enviroacoustics. This paper summarises the experimental procedure and results obtained to date.

![Figure 1 Simplified schematic showing the principle of the AE technique](image)

### 2. Three-point and Four-point fatigue tests

#### 2.1 Samples and materials properties

Eight notched bar specimens have been cut-off from rail steel (UIC 60 rails – 260 grade). Samples were rectangular in shape with dimension 100mm (L) x 10mm (W) x 10mm (H). The specimens were extracted from the web plane of the rail steel. All specimens were cut in the longitudinal orientation of the rail. The chemical composition of 260 rail steel is as indicated in Table 1. The nominal mechanical properties are summarised in Table 2 Mechanical properties of railway pearlite steel.

| Table 1 Typical chemical composition of pearlite rail steel grades |
|---------------|-----------|-----------|-----------|
| C      | Si      | Mn     | S     | P     | Cr  | Ni  | Mo  | V    |
| 0.55   | 0.2     | 0.60   | 0.018 | 0.013 | 0.25 | 0.25 | 0.10 | 0.03 |
| 0.78   | 1.9     | 1.5    | 0.037 | 0.035 | 0.50 | 0.05 |      |      |
Table 2 Mechanical properties of railway pearlite steel

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Fracture Toughness</td>
<td>35 MPa&lt;sup&gt;0.5&lt;/sup&gt;</td>
</tr>
<tr>
<td>Minimum Fracture Toughness</td>
<td>30 MPa&lt;sup&gt;0.5&lt;/sup&gt;</td>
</tr>
<tr>
<td>Minimum Tensile Strength</td>
<td>≥ 1.040 MPa</td>
</tr>
<tr>
<td>Brinell Hardness</td>
<td>≈ 330 HB</td>
</tr>
<tr>
<td>Yield Strength</td>
<td>≥ 608 MPa</td>
</tr>
<tr>
<td>Minimum Elongation Rate</td>
<td>9%</td>
</tr>
</tbody>
</table>

The optical micrograph in Figure 2 shows the typical microstructure of pearlite rail steel commonly used in modern rail grades.

![Microstructure of pearlite rail steel (1% Nital etch)](image)

Figure 2 Microstructure of pearlite rail steel (1% Nital etch)

2.2 Experimental Configuration

In order to initiate a crack and subsequently cause its crack growth during cycling fatigue loading samples were pre-cracked using a 4-point bending configuration. The specimens were set up on the Vibrophore pre-cracking fatigue machine as seen in Figure 3. Applied stress accumulated on the top of the notch region act as a driving force to extend the crack length during high-speed sinusoidal cyclic loading (~100Hz). The loading range was minimum 1.05kN and maximum 10.5kN (R=0.1). Crack growth was monitored using microscopy replicas.

![Sample pre-cracking using the Vibrophore fatigue machine](image)

Figure 3 Sample pre-cracking using the Vibrophore fatigue machine
When crack length reached a total length of 1mm the specimen was removed from the Vibrophore and set up on a Dartec 50 kN Servo-Hydraulic Universal Test Machine. Loads and position changed slowly rather than the Vibrophore machine due to the low frequency work conditions. To observe the applied load level and the number of cycles, 18 bit Phoenix Alpha digital control system and data acquisition unit is enabled after set up the specimen of which data logging direct from P.C. running Windows XP or Windows 7. Some of the samples were tested on an ESH 200kN Servo-Hydraulic Universal Test Machine used on the 20kN load range with an analogue control system.

Stress intensity factor (K) is dependent on the crack length, loading conditions and geometry of the sample. Equation 1 shows the relationship of K for 3-point bending and equation 2 for 4-point bending.

Relationship of K with stress, crack length and sample geometry

\[ K = \sigma Y \sqrt{a} \]  
\[ \sigma = \frac{3P \left( \frac{L - L_i}{2} \right)}{BW^{5/2}} \]

For 4-point bending test the equation is written as;

\[ K = \frac{3P \left( \frac{L - L_i}{2} \right)}{BW^{5/2}} f^{(a/W)} = \frac{3P \left( \frac{L - L_i}{2} \right)}{BW^{5/2}} Y \]

Where K is the stress intensity factor, P is the applied load, L and Li are the spans distances, B is the thickness of the sample W is the width of the sample and a is the crack length. The size of the specimen is given in Figure 12.
A commercial four-channel AE system manufactured by Physical Acoustics Corporation was employed during laboratory tests. The sensors used were two Pico wideband sensors with a bandwidth range between 150 kHz-750 kHz. The sensors were coupled to the surface of the sample using grease. The signal from the sensors was amplified using a PAC preamplifier using a 40dB gain. The data acquisition rate was set at $10^6$ samples per second. The Peak Definition Time (PDT) was set at 300µs, Hit Definition Time was set at 600µs and Heat Lockout Time (HLT) was set at 1000µs. As seen in Figure 5, cyclic trapezoidal loading was employed under 3-point and 4-point bending load during AE tests. R was kept at 0.1.

![Figure 5: Experimental configuration and trapezoidal load cycle](image)

Raw AE data were acquired using AEWin software supplied by PAC and were subsequently analysed using NOESIS software supplied by Envirocoustics (now Mistras Hellas). From the analysis of the AE results it was ascertained that noise from the machine was restricted to 40dB so any hits detected above that amplitude were almost entirely related to crack growth events. Figure 8 shows the amplitude versus time plot of hits and waveforms related to crack growth events for a four-point bending sample ($P_{\text{max}}=7.5\text{kN}, P_{\text{min}}=0.75\text{kN}, R=0.1$).
Figure 6 Amplitude versus time diagram. Bottom burst-type waveforms detected above 40dB related to crack growth events.

Figure 8 shows the number of vector hits with time. Hits recorded correspond to largely steady crack growth in this case followed by rapid propagation once the crack has reached a critical size and subsequently leading to final failure. Once a critical crack length has been reached substantial AE activity is recorded. Some high amplitude events are recorded at earlier stages of the experiment but they are few in number. However, the fact that high amplitude events are recorded occasionally is useful since it means that in the real life environment these events could be above the rolling noise of the passing trains.

Figure 7 Number of AE vector hits recorded versus time.
Figure 8 shows the crack length at 750 cycles using a microscopy replica.

Figure 8 The image taken from replica film to show the crack propagation

Figure 9 shows the distribution of the total number of vector hits with amplitude. It can be seen that there are several hits which have amplitude of 40dB. These are mostly related to machine noise. , and Figure 10 shows the density of hits with amplitude versus time.

Figure 9 Distribution of number of vector hits versus amplitude, and Figure 10 Density of hits with amplitude versus time

Figure 11 shows the duration of the recorded hits with time. It can be clearly seen that the events recorded after the crack has reached a critical size have the highest duration.
In general crack growth-related AE hits have higher duration than those related to noise. This factor can be used to filter out unwanted hits.

![Figure 11 Hit duration versus time](image)

Figure 11 Hit duration versus time

Figure 12 shows the four-point bending sample after final failure. The fatigue area at which the crack gradually with every loading cycle grew is clearly visible at the first 3mm. At that point the crack reached a critical size followed by rapid propagation and brittle fracture of the sample.

![Figure 12 Surface topography of the pearlite steel (SEM images)](image)
2.3 Simulated tests on rails with rolling noise present

In the field AE is expected to be affected by rolling noise produced from the wheels. Nonetheless, provided that the wheels are free of defects such as flats, metal build-up or rubbing flange then high-amplitude AE events due to crack growth are likely to be detectable even with the rolling noise present.

It is also important to recognise the influence of the amplification level employed. Therefore it may be useful to employ several sensors with different gains during such tests.

A customised four-channel AE system produced by Feldman Enterprises was used for these tests. One PAC AE wideband sensor with a bandwidth of 100 kHz-1MHz was employed in this case.

The signal was amplified by a PAC pre-amplifier and amplifier before being recorded using an Agilent 2531 data acquisition card. The data acquisition rate was set at 500 kHz and data were recorded for duration of 5-10 seconds depending on the test. Data were logged by a PC using a customised data logger also provided by Feldman. AE data were analysed using Feldman’s PCM software.

During initial tests a single laboratory-sized wheel (0.16m diameter) was rotated manually on a small section of rail. The average wheel moving speed was 1 m/s. The AE sensor was coupled on the rail using grease and kept in place under constant load using magnetic hold-down. Figure 13 shows the experimental configuration employed.

Figure 13 Experimental configuration for simulated AE tests

Figure 12 shows the raw AE waveform associated with rolling noise from the wheel using very low gain (23dB). The associated moving RMS plot is shown on the right.
It was decided that it may be possible to simulate a crack growth event by using a pencil break. A pencil break produces a similar AE waveform with that produced by fast crack growth. A pencil break event without any rolling noise and associated RMS is shown in figure 13.

During testing, the pencil tip was broken on the rail while the wheel was rolling on the rail section. Further tests were carried out using a rail trolley shown in Figure 14 at Birmingham University’s test track. The rail trolley is motorised so it was moved along the track using its motor.
The test trolley was run at a maximum speed of 3km/h due to the restricted length of the rail track. The recorded raw AE signals and RMS with the pencil break event present are shown in Figure 15.

![Figure 14 Experimental configuration on the test rail track at University of Birmingham](image)

**Figure 14 Experimental configuration on the test rail track at University of Birmingham**

**Figure 15 Raw AE signal and RMS with clearly visible pencil break event simulating a crack growth event. Gain is set at 58dB**

### 3. Conclusions

The results reported in this paper show that it is possible to clearly identify the nature of waveforms related to crack growth in rail steel. Furthermore it has been shown that wheel related rolling noise may not be a barrier for the detection of crack growth in the field. Initial tests have shown that AE is a promising technique for the detection of crack growth in defective in-service rails. The level of amplification is likely to be of critical importance. The signal processing of acquired AE waveforms need to be researched further to develop suitable filtering techniques in cases where AE waveforms related to crack growth have similar amplitude to that of background noise produced by wheel rolling.
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References