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Detection of crack growth in rail steel using acoustic emission

Andrii Kostryzhev
University of Wollongong, andrii@uow.edu.au

C L. Davis
University of Birmingham

C Roberts
University of Birmingham

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Increased traffic speeds and axle loads on modern railways enhance rail track degradation. To eliminate track failure due to rail defects, a condition monitoring system requires methods for the early detection of defects which grow in service. Acoustic emission (AE) monitoring is the only non-destructive technique which might be applied online to study the defect growth under traffic loading. However, a high level of traffic noise and a limited signal from crack growth, especially at low crack growth rates, significantly complicate the AE signal analysis. In the present work, the AE monitoring of rail steel fatigue was carried out in a 'noisy' laboratory environment using different methods of signal analysis. Signal parameters of AE for machine noise, sample deformation and crack growth were identified. The crack growth related AE signature was found to be dependent on fracture mode.

Keywords
rail, steel, crack, acoustic, growth, emission, detection

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Detection of Crack Growth in Rail Steel Using Acoustic Emission

A.G. Kostryzhev,
Research Fellow, School of Mechanical, Materials and Mechatronics Engineering,
University of Wollongong, NSW, 2522, Australia
(at the time of this work was Research Fellow, School of Electronic, Electrical and Computer Engineering,
University of Birmingham, Edgbaston, Birmingham, B15 2TT, United Kingdom)

C.L. Davis,
Professor, School of Metallurgy and Materials,
University of Birmingham, Edgbaston, Birmingham, B15 2TT, United Kingdom

C. Roberts,
Professor, School of Electronic, Electrical and Computer Engineering,
University of Birmingham, Edgbaston, Birmingham, B15 2TT, United Kingdom

Abstract

Increased traffic speeds and axle loads on modern railways enhance rail track degradation. To eliminate track failure due to rail defects, a condition monitoring system requires methods for the early detection of defects which grow in service. Acoustic emission (AE) monitoring is the only non-destructive technique which might be applied on-line to study the defect growth under traffic loading. However, a high level of traffic noise and a limited signal from crack growth, especially at low crack growth rates, significantly complicate the AE signal analysis. In the present work, the AE monitoring of rail steel fatigue was carried out in a "noisy" laboratory environment using different methods of signal analysis. AE signal parameters for machine noise, sample deformation and crack growth were identified. The crack growth related AE signature was found to be dependent on fracture mode.

Key words: acoustic emission, fatigue, rail steel

INTRODUCTION

Acoustic emission (AE) monitoring has been shown to be a reliable method for detecting the onset and growth of fatigue cracks in steel [1]. The AE count rate, defined as the number of threshold crossing counts per unit time or deformation cycle, has been widely accepted [1 - 6] as an indicative parameter for crack growth (Fig. 1). However, the absolute number of AE events and AE count rate during fatigue testing depend on the steel microstructure and mechanical properties [1, 2, 7], mode of loading and sample geometry [8, 9], and whether there is the presence of a chemically aggressive environment [10, 11]. Signal analysis becomes more complicated if processes other than crack growth, such as sample deformation, friction or machine work, cause an increased AE of background noise.

An increase in capacity (higher travel speeds and axle loads) on modern railways increases the dynamic loading on rails and track degradation. To maintain high levels of safety for railway operations, condition monitoring of rail tracks requires methods for the early detection of rolling contact fatigue (RCF) cracks and their growth in service. AE offers a technique for monitoring whether crack growth is occurring under traffic loading. It is known that fatigue cracks can grow slowly after on-set and may not produce a great number of AE events [2, 12] that can be easily distinguished from background noise using the AE count rate only. Thus substantial analysis of the acoustic emission parameters is needed for crack signal separation from noise; in particular, quantitative characteristics of each acoustic waveform associated with crack growth. In the present work, AE monitoring of rail steel fatigue was carried out in a "noisy" laboratory environment, i.e. with the presence of high emission from the loading machine and plastic deformation of the test sample, to determine whether the crack growth signal characteristic could be identified.

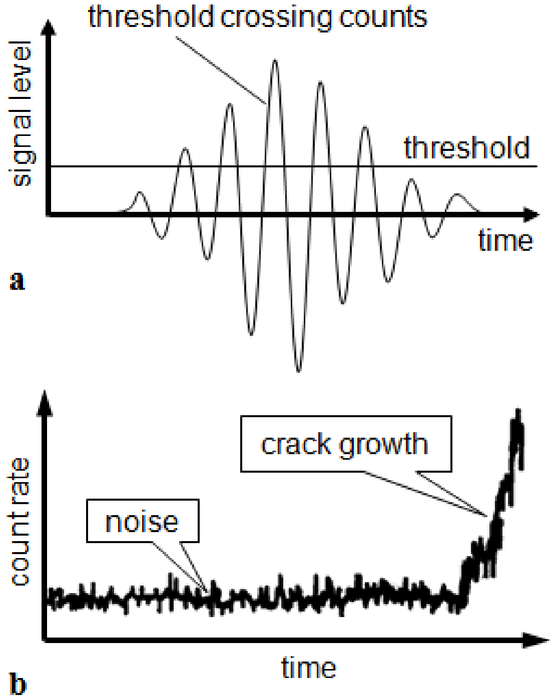

Figure 1. **a** AE hit and **b** AE count rate vs time for 0.77 C-0.84 Mn-0.29 Si-0.21 S rail steel under constant load amplitude testing [4]

MATERIALS AND EXPERIMENTAL TECHNIQUES

Rectangular bar shaped samples of 260 rail steel grade (0.7 C-0.2 Si-1.0 Mn-0.4 Cr, all wt%) were cut from new rails. A centre notch of 30^0 angle and 4 mm depth was machined perpendicular to the rail web plane (Fig. 2 a). Three point bend fatigue tests of one pre-cracked and two non pre-cracked samples were carried out on an Amsler 100 kN vibrophore machine, using cyclic loading of min/max load ratio of R = 0.06 and starting frequency 79 Hz (Fig. 2 b). A mean load was applied by the static load motor, which has an AE noise level below the 30 dB threshold set for the tests. The dynamic loading was applied by a separate (electromagnetic) motor, the AE noise level from which is above the 30 dB threshold set. Acoustic emission was recorded on an industrial hardware station using 2 broadband differential piezoelectric sensors, 2 preamplifiers of 2/4/6 type and AEWin for PCI2 version E3.61 software, produced by Physical Acoustics Corporation (USA). The AE signal analysis was carried out using AEWin and Noesis version 5.3 software, developed by Envirocoustics S.A. (Greece). The on-set of crack growth and crack length monitoring was carried out using imaging of sample surface replicas; the imaging was carried out using an Olympus CH-2 optical microscope. To determine the operating fracture mode, the fracture surface after testing was assessed; a total area of 6.1 mm^2 was imaged using a Leica DMRX optical microscope and 15.9 mm^2 was imaged using a Philips-XL30 scanning electron (SEM) microscope.

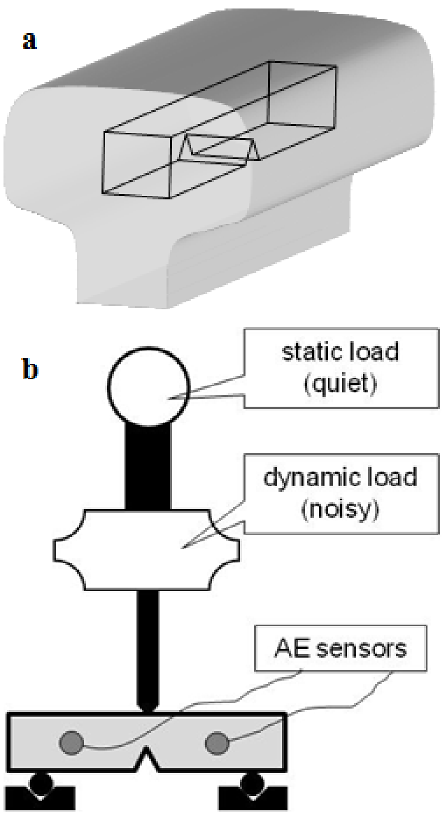

Figure 2. Scheme of **a** sample cutting and **b** loading during fatigue testing

RESULTS AND DISCUSSION

Monitoring of acoustic emission during fatigue of non pre-cracked samples has shown a significant change in AE response after crack on-set (approx. 2100 sec. test time in Fig. 3). As seen from the single hit amplitude - test time - duration distribution (Fig. 3 a) after crack on-set:

- AE greatly decreases within the < 50 dB amplitude range;
- AE of more than 3 times higher energy and duration appears within the > 65 dB amplitude range and increases in the hit number density as the crack is growing.

Analysis of the average hit feature variations with test time has shown that after crack on-set:

- AE count rate increases (from 125,000 to 200,000 during a selected 500 sec. test time period on Fig. 3 b);
- Amplitude does not show a significant change (Fig. 3 c);
- RMS, rise time and absolute energy may have random peaks of up to 10 times higher than the test period before crack on-set (Fig. 3 d, e, f);
- Average frequency increases (from below 100 kHz before crack on-set to up to 150 kHz after crack on-set during a selected time period on Fig. 3 g).

As seen from Fig. 3, after crack on-set the AE count rate, average frequency, RMS, rise time and absolute energy show a significant variation from the background noise level and thus could be recommended for monitoring crack growth in a “noisy” environment. However, in the present study the “reasonable variation” of these parameters was observed after about 20,000 fatigue cycles from crack on-set, i.e. when the crack growth rate reaches significant values. In practice the crack is growing by short increments, which produce a limited level of AE. Therefore, a single hit waveform analysis will be required to indentify the crack growth at low rates.

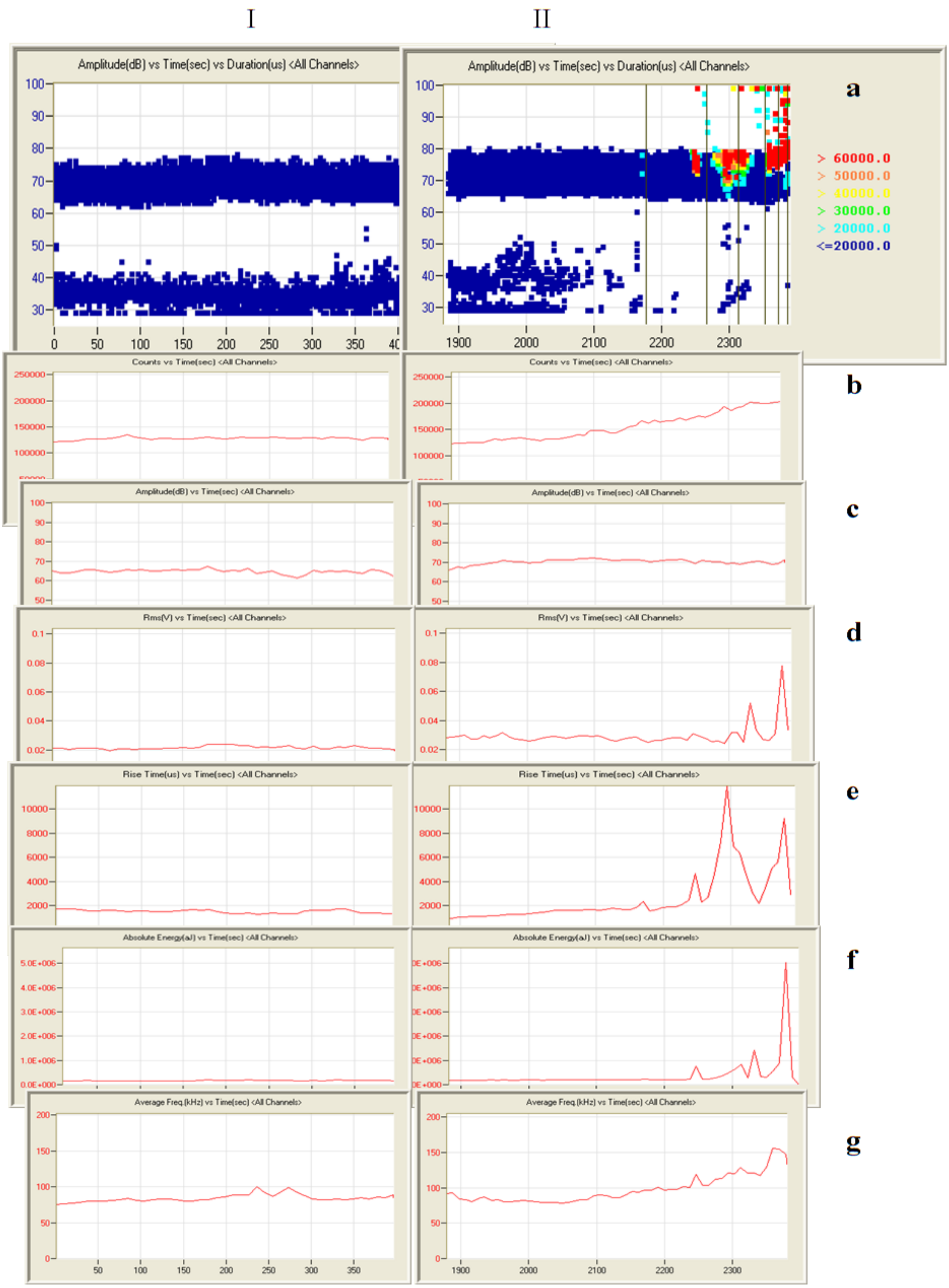

Figure 3. AE response recorded during fatigue of a non pre-cracked sample: I is a time period before crack on-set, II is a time period which includes crack on-set; **a** hit amplitude, dB – test time, sec – hit duration, μs distribution (each vertical line mark shows a loading frequency drop of 1 Hz from the initial test frequency of 79 Hz); **b** count rate, s^{-1}; **c** average amplitude, dB; **d** RMS, V; **e** rise time, μsec; **f** absolute energy, aJ; **g** average frequency, kHz

In the present study, the AE signal analysis has shown a variety of waveform and power spectrum shapes. With respect to a possible cause of the AE, three zones have been distinguished on the amplitude-duration distribution (Fig. 4, Table 1):

- Zone 1 is likely to be due to machine noise; AE in this zone is present throughout the test. Disappearance of the low amplitude part of the machine noise signal after crack on-set can be related to a decrease in sample stiffness and a variation in loading frequency and loading amplitude, as the vibrophore keeps up constant loading force;
- Zone 2 is likely to be due to plastic deformation (dislocation motion) of the sample; AE in this zone increases before crack on-set, due to stress concentration around the notch tip, and decreases after crack on-set, due to a decrease in deformed volume in front of the sharp crack tip [13]. Fretting on the fracture surface during crack closure is also possible in this zone [2, 16];
- Zone 3 is likely to be due to crack growth; AE in this zone appears after crack growth on-set. Two major AE signatures were observed in this zone: low frequency with high duration (zone 3a) and high frequency with low duration (Zone 3b), which are expected to be due to ductile and brittle fracture modes respectively [14, 15].

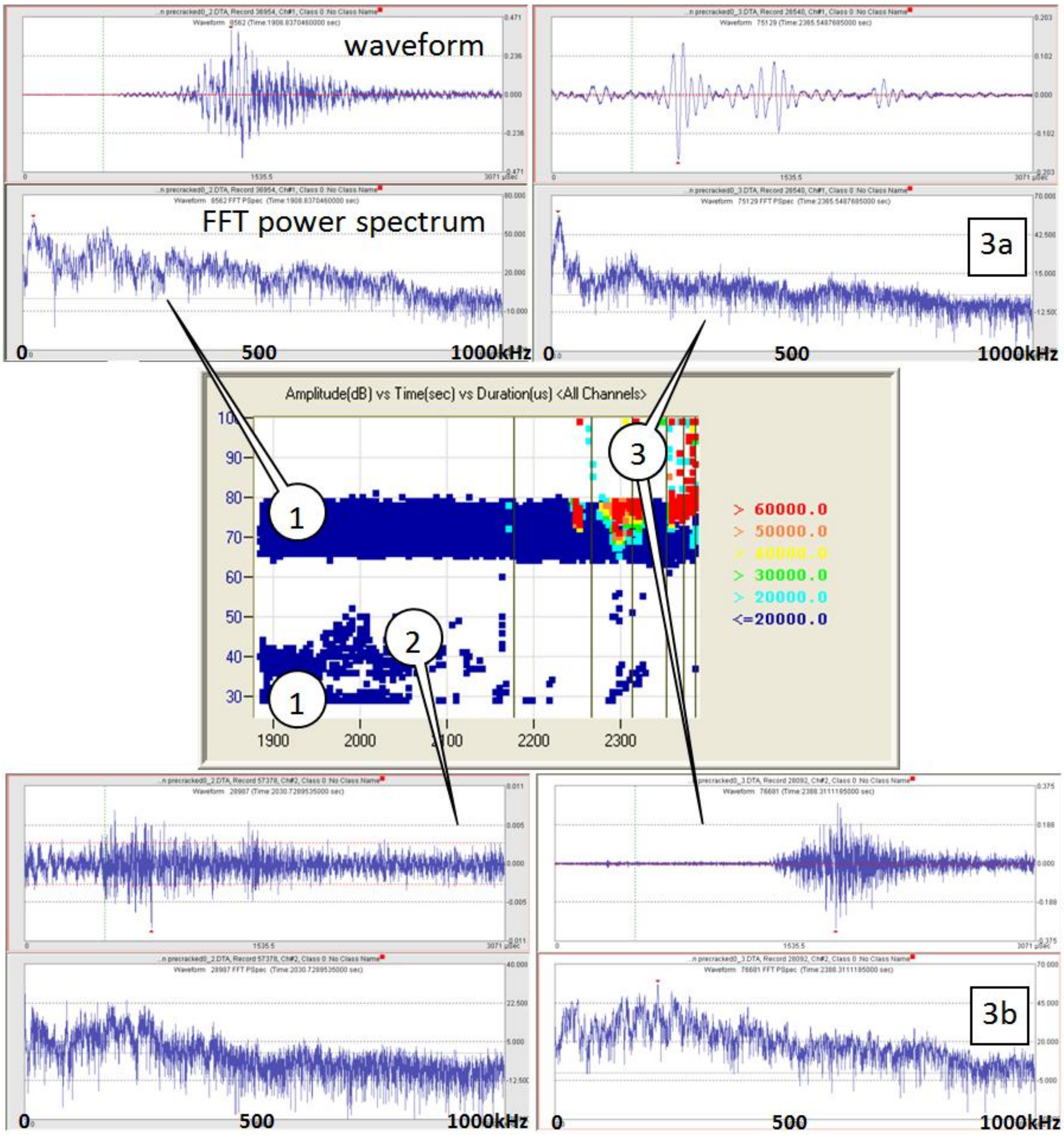

Figure 4. Waveforms and FFT power spectra for different AE zones on the amplitude, dB – test time, sec – wave duration, μsec distribution during crack on-set and growth (each vertical line mark shows a loading frequency drop of 1 Hz from the initial test frequency of 79 Hz). A description of the different regions (marked 1 – 3 a/b) is given in Table 1.

Peak frequencies for brittle crack growth, observed in the tested fully pearlitic steel, are higher than those for deformation (Table 1). This corresponds to the data obtained for other steel grades [12, 17, 18]. Peak frequencies for deformation of fully pearlitic steel (50-200 kHz, Table 1) are higher than those for fully ferritic steel (< 50 kHz [18]) and are in the same range as for dual phase steel (<100 kHz [12], 150 – 175 kHz [17]). Peak frequencies for brittle crack growth in the pearlitic steel (200 – 250 kHz, Table 1) are lower than those for brittle crack growth in dual phase steel (550 – 600 kHz [17]). Peak frequencies for ductile crack growth in the pearlitic steel (< 50 kHz, Table 1) are lower than those for ductile crack growth in dual-phase steel (100 – 120 kHz [17]) and are in the same range as for the plastic deformation of fully ferritic steel (< 50 kHz [18]). These could be explained by the differences in steel chemistries, microstructures and mechanical properties, fracture development mechanisms and test parameters (mode of loading, stress factor and loading frequency).

Table 1 AE waveform parameters during fatigue of a non pre-cracked sample.

Zone, Fig. 4		Suggested cause of AE	Amplitude, dB	Duration, ms	FFT power spectrum frequency peaks, kHz
1		machine noise	< 35 and 65-80	< 20	< 50
2		sample deformation	35 - 50	< 20	50 - 200
3	a	ductile crack growth	> 65	> 60	< 50
	b	brittle crack growth	> 65	> 20	200 - 250

SEM imaging of the sample fracture surfaces after testing revealed a quasi-cleavage fracture mechanism, Fig. 5, which comprises brittle (cleavage) and ductile (shearing) fracture modes and is typical for fully pearlitic steels [14, 15, 19, 20]. Two fracture modes, brittle and ductile, correspond to two AE signatures recorded within the > 60 dB zone. These are: long duration low frequency AE signals (Fig. 5 b) for ductile fracture mode and short duration high frequency AE signals (Fig. 5 c) for brittle fracture mode.

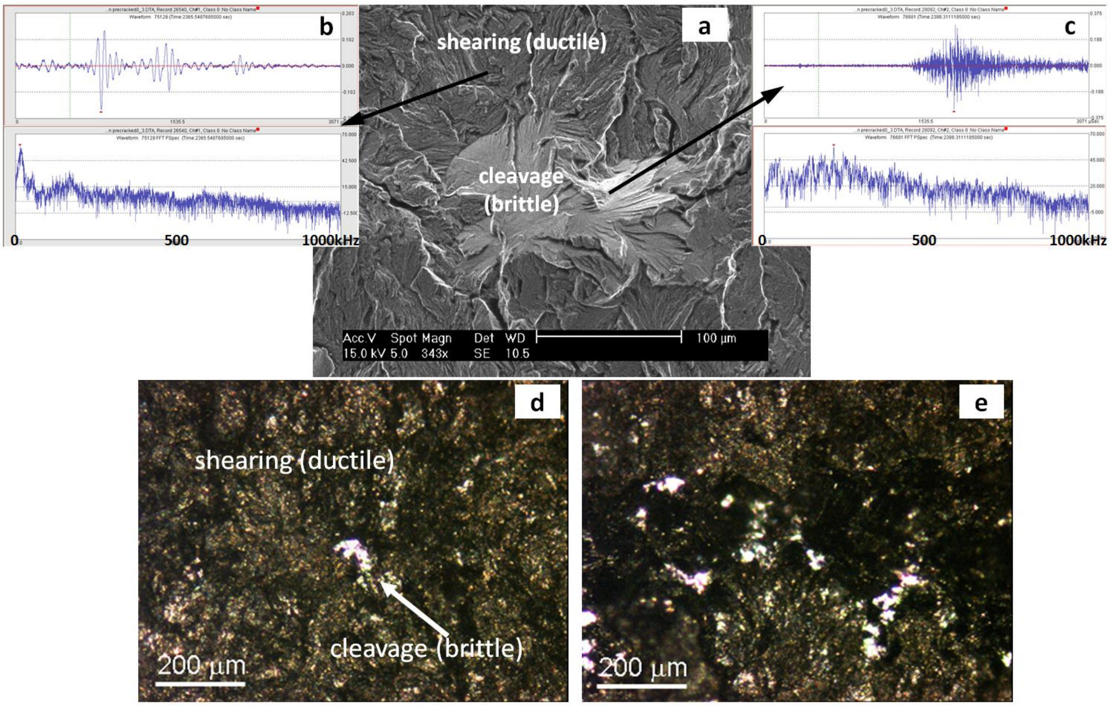

Figure 5. Typical **a** SEM image of the fracture surface after fatigue and corresponding AE waveforms and power spectra for **b** ductile and **c** brittle fracture modes; typical optical images of the fracture surface **d** after crack on-set (test time period from 2100 sec. to 2350 sec. in Figs 3 and 4) and **e** during the period of steadily increasing crack growth rate (test time period from 2350 sec. to 2400 sec. in Figs 3 and 4)

Optical imaging of the sample fracture surfaces has shown an increase in the amount of cleavage facets (bright areas in Fig. 5 d and e) with an increase in test time after crack on-set, i.e. with an increase in crack length, stress factor and crack growth rate. This corresponds to an increase in the number of short duration high frequency AE hits/waves (Fig. 3 a), which are indicative of the brittle fracture mode, and a slight increase in the AE average frequency (Fig. 3 g).

CONCLUSIONS

Acoustic emission monitoring of the rail steel fatigue and fractures has demonstrated:

1. After fatigue crack on-set the AE signal features (such as average frequency, RMS, rise time and absolute energy) show a level of variation which may be sufficient enough for crack growth detection. However, in a noisy environment and at a low crack growth rate the AE single hit waveform and power spectrum analysis should be recommended as a more effective methodology.
2. AE power spectrum peak frequencies for deformation of steel with a fully pearlitic microstructure were observed to be in the range of 50 – 200 kHz, which is higher than those for steels with a fully ferritic microstructure and is at the same level as for steels with a ferrite-martensite microstructure.
3. The AE signal, associated with crack growth, depends on the fracture mode: high duration, low frequency signals result from ductile fracture; low duration, high frequency signals result from brittle fracture. In the fully pearlitic steel the AE power spectrum peak frequencies for ductile fracture were observed to be below 50 kHz and for brittle fracture to be above 200 kHz.
4. A number of low duration high frequency AE hits/waves qualitatively follows the number of cleavage facets, i.e. the amount of brittle fracture.

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REFERENCES

1. A.C.E. Sinclair, D.C. Connors and C.L. Formby: *Mat. Sci. Eng.*, 1977, **28**, 263 – 273.
2. T.C. Lindley, I.G. Palmer and C.E. Richards: *Mat. Sci. Eng.*, 1978, **32**, 1 – 15.
3. M.N. Bassim, M. Dudar, R. Rifaat, R. Roller: *IEEE Transactions on Power Delivery*, 1993, **8**, № 1, 281 – 284.
4. M.N. Bassim, S.S. Lawrence and C.D. Liu: *Eng. Fract. Mech.*, 1994, **47**, № 2, 207 – 214.
5. K. Nam: *Fatigue Fract. Eng. M.*, 1999, **22**, 1103 – 1109.
6. T.M. Roberts and M. Talebzadeh: *J. Constr. Steel Res.*, 2003, **59**, 679 – 694.
7. Y.B. Guo and D.W. Schwach: *Int. J. Fatigue*, 2005, **27**, 1051 – 1061.
8. M.N. Basim and M. Houssny-Emam: *Mat. Sci. Eng.*, 1984, **68**, 79 – 83.
9. T.M. Roberts and M. Talebzadeh: *J. Constr. Steel Res.*, 2003, **59**, 695 – 712.
10. S. Yuyama, T. Kishi and Y. Hisamatsu: *Nucl. Eng. Des.*, 1984, **81**, 345 – 355.
11. D.J Buttle and C.B. Scruby: *NDT Int.*, 1989, **22**, № 2, 81 – 96.
12. V. Chaswal, G. Sasikala, S.K. Ray, S.L. Mannan and B. Raj: *Mat. Sci. Eng. A*, 2005, **395A**, 251 – 264.
13. Y. Iino, *Eng. Fract. Mech.*, 1975, **7**, 205 – 218.
14. J. Toribio, A.M. Lancha and M. Elices: *Mat. Sci. Eng. A*, 1991, **145**, 167 – 177.

15. F. Wetscher, R. Pippan and R. Stock: Proc. 16th European Conference of Fracture, Alexandroupolis, Greece, 3-7 July 2006, Springer, Netherlands, 2006, 859 – 860.
16. D.H. Kohn, P. Ducheyne and J. Awerbuch: *J. Mater. Sci.*, 1992, **27**, 3133 – 3142.
17. R. Khamedi, A. Fallahi and H. Zoghi, *International Journal of Recent Trends in Engineering*, 2009, **1**, № 5, 30 – 34.
18. A. G. Kostryzhev, R. B. Punch, C. L. Davis and M. Strangwood, *Mater. Sci. Tech*., 2012, **28**, № 2, 240 - 242.
19. E. M. Taleff, J. J. Lewandowski, and B. Pourladian, *JOM-US*, July 2002, 25 – 30.
20. J. Toribio, B. González, J.-C. Matos, *Ciência e Tecnologia dos Materiais*, 2008, **20**, № 1-2, 68 – 74.