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ACOUSTIC EMISSION STUDY OF FATIGUE CRACK GROWTH IN RAIL TRACK MATERIAL

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ABSTRACT

The fatigue crack growth behavior of longitudinal crack in rail steel was investigated using the compact tension, (CT) specimen. The fatigue crack growth rate curve, *da/dN* as a function of stress intensity factor range, ΔK was plotted in order to analyze the crack growth properties of rail material. The CT specimen was tested by means of tension-tension stresses with load ratio of 0.1 while simultaneously recording the acoustic emission, (AE) signal. The acoustic emission count rate associated with the stress intensity factor was obtained to understand acoustic emission behavior corresponding to the fatigue crack growth. The result indicates that the constant values of C and m according to Paris Law equation, $da/dN = C(\Delta K)^m$ are 2.63×10^{-12} and 3.29, respectively. The acoustic emission count rate equation becomes $dn/dN = 2.63 \times 10^{-7} (\Delta K)^{3.51}$. The linear relationship between crack growth rate and AE count rate will give $\log(da/dN) = 0.738 \log(dn/dN) - 5.815$. Based on these correlations it may possible to monitoring fatigue damage of short term acoustic emission monitoring.

***Keywords**:* Acoustic emission (AE), AE count, Fatigue, Crack growth, Rail track.

INTRODUCTION

A modern study of fatigue phenomena in railway track material has been started since 1950's. A lot of studies were implemented in order to investigate the fatigue phenomena and at the same time reducing the accidents involves on railway (Azuan, 2009). Fatigue fracture of rails is a rather complex issue since the rail is among the important transportation. Various aspects such as highly complex variable loading, secondary stresses and seasonal changes of the environmental conditions have to be taken into account because all these things will contribute in fatigue fracture of rails. Rails are subjected to primary and secondary loading components. The loading by the wheel is applied as bending stress, σ_b, axial stresses, σ_m , and Hertzian pressure, p, from rolling contact(Aglan and Gan, 2001).

Fatigue cracks can be described as sudden and catastrophic structural collapse, when the applied load and crack dimension are such that the stress intensity factor, ΔK, on the crack tip reaches the critical value, typical of the material (Riemelmoser and Pippan, 2002). Stress control and strain control test have been commonly used to study the fatigue crack propagation behavior. The traditional approach to fatigue resistant design in based on *S-N* curves but it does not provide any indication of the rate at which fatigue cracks are likely to develop (Parker, 1981). During fatigue the crack growth, *a*, for *N*, fatigue cycles with the stress intensity factor, ΔK, and follows the Eq. (1) that can be described by the Paris-Erdogan's law (Maddox, 1991):

$$\frac{da}{dN} = C(\Delta K)^m \quad (1)$$

Where *a*, is a representative crack length, *N* is the number of fatigue cycles, ΔK is the applied stress intensity factor range and *C* and *m* are assumed to be constant for a particular material. Eq. (1) can also be expressed in logarithmic form as:

$$log\left(\frac{da}{dN}\right) = logC + m\ log\Delta K \quad (2)$$

During past the 20 years, acoustic emission (AE) technique has become a reliable and an effective technique non-destructive technique (NDT) for detection, location and monitoring of fatigue cracks in a variety of metal structures. Acoustic emission (AE) is the class of phenomena whereby transient elastic waves are generated by the rapid release of energy from localized sources within a material, or the transient elastic waves so generated. Other terms for this phenomenon are stress wave emission and micro-seismic activity (Kalyanasundaram et al., 2007). Sources of AE are defect related processes such as crack extension and plastification of material in highly stressed zone adjacent to the crack tip (Fang and Berkovits, 1995). The AE capable to measure crack closure during fatigue cycling, and it is possible to compare the result obtained through AE signal with other NDT, such as crack opening displacement method, back face strain gauge method and surface strain method (Lee et al., 1996).

A great number of studies of AE have focused on the correlation some characteristic signals parameters, such as amplitude, count or energy and the behavior or the material. The AE count is the number of times the AE exceeds a preset threshold during testing. Previous studies have identified the AE count as a useful scalar measure of damage under cyclic loading (Biancolini et al., 2006). Several authors showed the relationship between AE count rate and stress intensity factor in form power law similar to the Paris-Erdogan law that expressed as (Bassim et al., 1994):

$$\frac{dn}{dN} = B(\Delta K)^p \quad (3)$$

or

$$log\left(\frac{dn}{dN}\right) = logB + p\ log\Delta K \quad (4)$$

where *n* denotes the number of counts and *B* and *p* are assumed to be constant for a particular material. These power laws provide a natural link between non-destructive AE monitoring and qualitative fracture mechanics methods for predicting the rate of crack propagation. Besides, the AE count rate shows reliable correlation with the crack growth ratio. Equation (2) and (4) imply a linear relationship between the log of the crack propagation rate *da/dN* and the log of the acoustic emission count rate *dn/dN*, which enables the prediction of fatigue life based on short monitoring of AE and give an equation (Roberts and Talebzadeh, 2003a):

$$log\left(\frac{da}{dN}\right) = q log\left(\frac{dn}{dN}\right) + logD \quad (5)$$

The characteristic of AE signals associated with the fracture mechanics parameters can used to provide damage evaluation of the material. Taking account of these considerations, the goal of this paper is to identify fatigue crack growth properties in compact tension specimen made from rail track material, and to study the AE count rate of the crack growth in different region.

EXPERIMENTAL DESIGN

Test Specimens

Compact tension specimen was prepared from the railway track material in accordance with the standard dimensions in the standard ASTM E647. The specimen was cut by following the Short Transverse-Longitudinal (S-L) plane with the loading aligned in perpendicular to the crack direction. The chemical composition and mechanical properties of the railway track material are shown in Table 1 and Table 2. The specimen was prepared introducing a notch with height of W/16 = 3mm. The notch length was 22.81 mm measured from the front face of the specimen and 9.81 mm measured form the pin holes centerline. The notch of specimen was machined using electrical discharge machining (EDM), which produces significantly lower residual stresses than mechanical milling (ASTM E647 2003). The specimen was polished with different grade of sand paper to permit observations of the crack path. The detail geometry of the specimen is illustrated in Figure 1.

Test Procedures

The compact tension specimen was tested using Instron-Material Test System model MTS 810 servo-hydraulic machine, which is a closed-loop loading system with a load cell enabled to sustain the maximum load capacity of 250 kN. The specimen was subjected to cyclic tension-tension loading in the sinusoidal wave shape. The fatigue precracking was conducted on the specimen before testing to provide a sharpened fatigue crack of adequate size and straightness. The fatigue crack growth rate was performed under load control at a constant load ratio (ratio of minimum to maximum load) of R = 0.1, at a sinusoidal frequency of 10 Hz. All testing were performed in ambient laboratory air (temperature: 20 - 25 ^{o}C) with a relative humidity in the range of 40 - 75 percent. The crack length was measured at both sides (front and back) of the specimen using optical microscope with a magnification of 10 and accuracy of 0.01 mm. Acoustic emissions from the test specimen were monitored and recorded by Vallen Systeme GmbH, as described in the following section.

Acoustic Emission Monitoring

Acoustic emission monitoring of fatigue crack was performed using Vallen Systeme GmbH (AMSY5). The AE signals were detected by using a wide band piezoelectric sensor with frequency range from 350 kHz to 2MHz. The acquired AE signals were amplified by a 34 dB fixed gain preamplifier, with a sampling rate of 5 MHz. The piezoelectric sensor was placed near the tip of fatigue pre-crack. In order to maintain full face contact, i.e. avoid movement between the piezoelectric sensor and the specimen surface, heavy duty vacuum grease was used as a coupling medium. After the installation of the sensor, a pencil lead break procedure, a method known as the Hsu-Nielson method was performed to simulate AE signals in the calibration of AE system. To determine the threshold level, the sensor was attached on a specimen placed in loading frame. Then, several tentative levels of were applied while the hydraulic power was turned on. At the threshold level of 30 dB, no background noise was observed, even though the hydraulic power supply was turn on. The schematic description of the overall experimental setup is shown in Figure 2.

Table 1: Chemical composition of rail track material.

Element	C	Mn	Si	P	S	Cr+Mo+Ni +Cu+V
Content % (weight)	0.6 ~ 0.8	0.83 ~ 1.30	0.1 ~ 0.5	< 0.05	< 0.05	< 0.35

Table 2: Mechanical properties of rail track material.

Mechanical Property	**Unit**	**Value**
Yield Stress	MPa	825
Ultimate Tensile Stress	MPa	923
Elongation	%	13

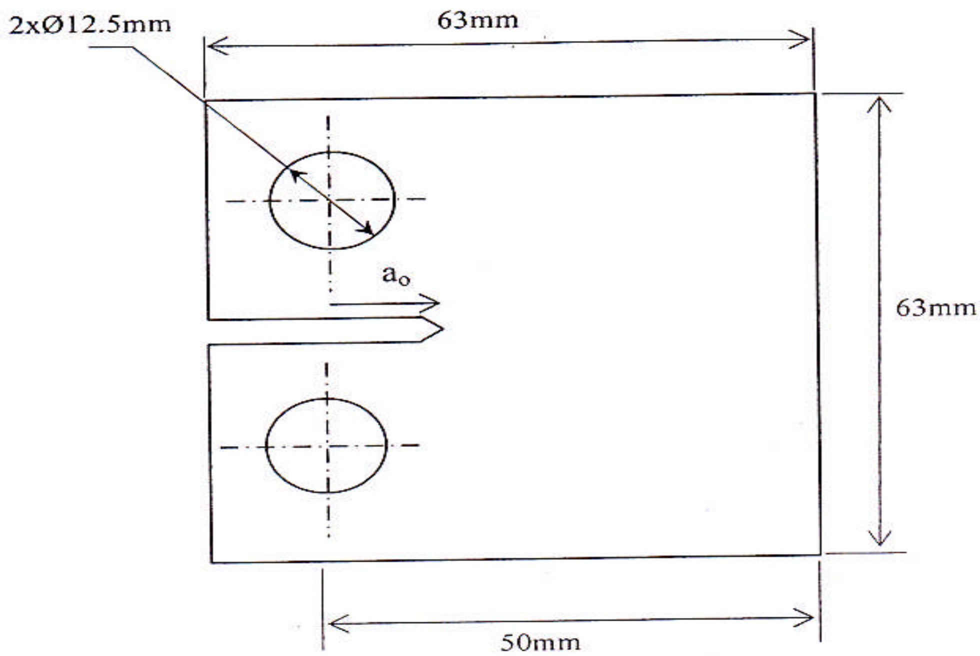

Figure 1: Details of compact tension specimen.

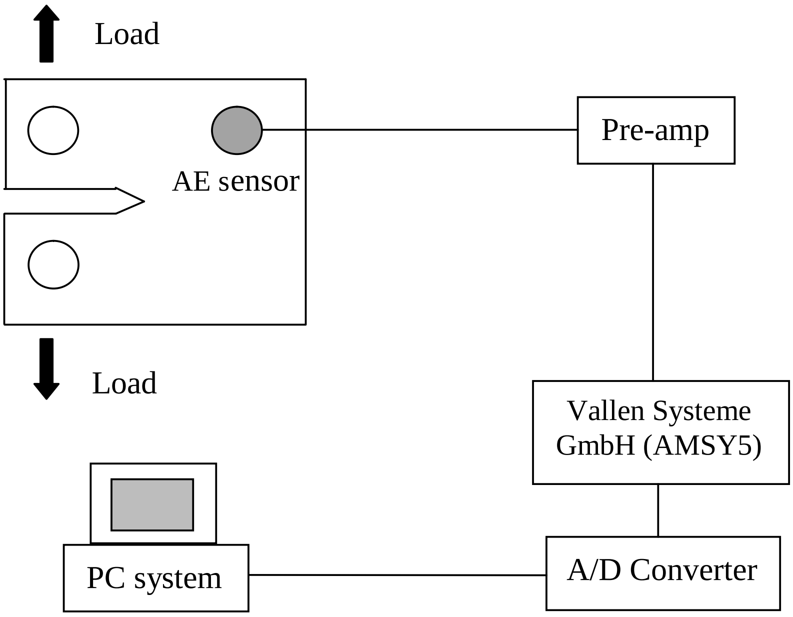

Figure 2: Schematic diagram of the overall experimental setup.

RESULTS AND DISCUSSION

A plot of crack length, *a*, versus the number of cycles, *N*, for the rail track material had been shown in Figure 3. It can be seen from Figure 3 that total life fatigue lifetime of the rail track material is approximately 370,000 cycles. The initiation lifetime was about 250,000 cycles and the propagation lifetime is about 340,000 cycles. The crack length grew up to about 0.68 mm after initiation. The crack propagation very fast in the last several hundred cycles, and the critical length reach about 1.6 mm.

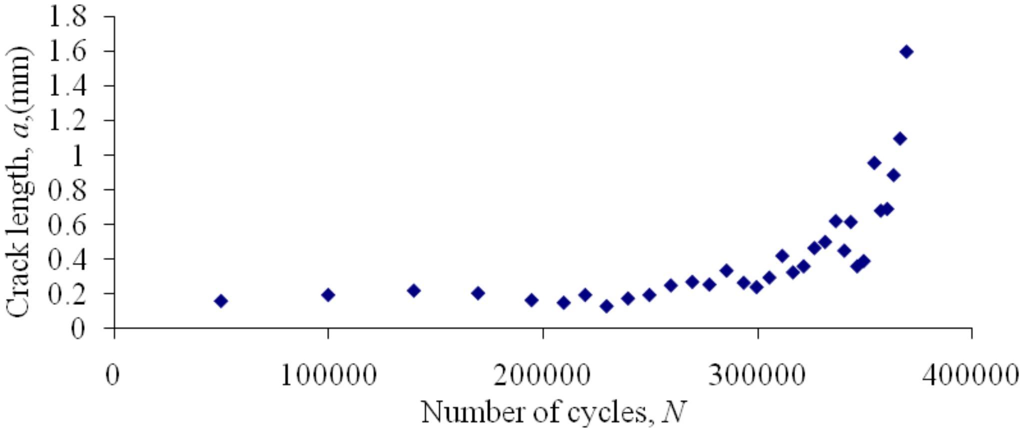

Figure 3: Plot of crack length, *a*, versus number of cycles, *N*.

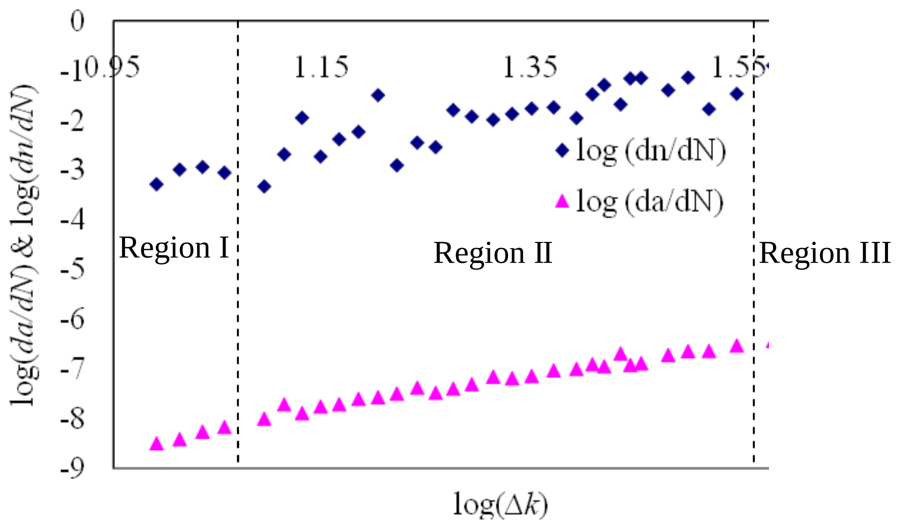

Figure 4: The relationship of AE count rate log(*dn/dN*) and crack growth rate log(*da/dN*) with stress intensity factor log(Δ*K*).

Analysis of crack growth data is based on relationship between log(*da/dn*) versus log(Δ*K*), as shown in Figure 4. Basically, the graph can be divided into three region; region I (threshold), region II (Paris) and region III (rapid fracture). In region I is at threshold region, $\Delta K = K_{th}$, the crack will propagate with very low speed or the crack does not start to grow until Δ*K* reaches a critical value. The threshold region is not associated with non-propagating microcracks but associated with the growth of macrocracks. These microcrack were nucleated at material surface but could not penetrate into the material (Chang et al., 2009). In region II, the crack growth rate increase linearly with increasing of Δ*K*. The crack is of detectable size and grows in such a way. In region III, the crack increases rapidly to failure. The crack in region II can be presented with power function of Δ*K*, leading to a linear relation between log(*da/dn*) and log(Δ*K*), and can be represented by Eq.(2). The best fit line had been drawn in region II in order to determine the constant value of *C* and *m* according to Paris Law. Hence, Eq. (2) which defines the crack propagation rate, becomes

$$log\left(\frac{da}{dN}\right) = 3.29 log(\Delta K) - 11.58 \qquad (6)$$

Figure 4 also shows the relationship between the AE count rate, log(*dn/dN*) and the stress intensity factor, log(Δ*K*). It could be seen that the AE count rate and the crack growth rate were increased almost linearly with log(Δ*K*). The AE signals generated by the crack growth during region I had the first longitudinal wave whose amplitude were too low to meet the threshold criteria set in the AE system. In other words, the AE system was activated only by the Rayleigh surface wave of the AE signal whose amplitude was much higher than that of the longitudinal wave (Chen and Choi, 2004). This is the reason why the AE count rate is lower in region I rather than other region. The AE count rate increases with increase in log(Δ*K*) during region II. It was attributed to the increase in size of the cyclic plastic zone which is generated and developed only under plane strain conditions (Murav'ev et al., 2002). The higher AE count rate also was attributed to irreversible cyclic plasticity with extensive multiplication and rearrangement of dislocation taking place within the cyclic plastic zone (Kalyanasundaram et al., 2007). The AE count rate was founded to be strongly dependent on the combination of the volume of the cyclic plastic zone, average plastic strain range and the number of cycles before crack extension (Roberts and Talebzadeh, 2003b). Based on this, an empirical relationship between the cumulative AE count rate, log(*dn/dN*) and log(Δ*K*) was proposed similar to the Paris-Erdogan law by the Eq. (4). Then, it can be expressed after determine the constant value as:

$$log\left(\frac{dn}{dN}\right) = 3.51log(\Delta K) - 6.58 \quad (7)$$

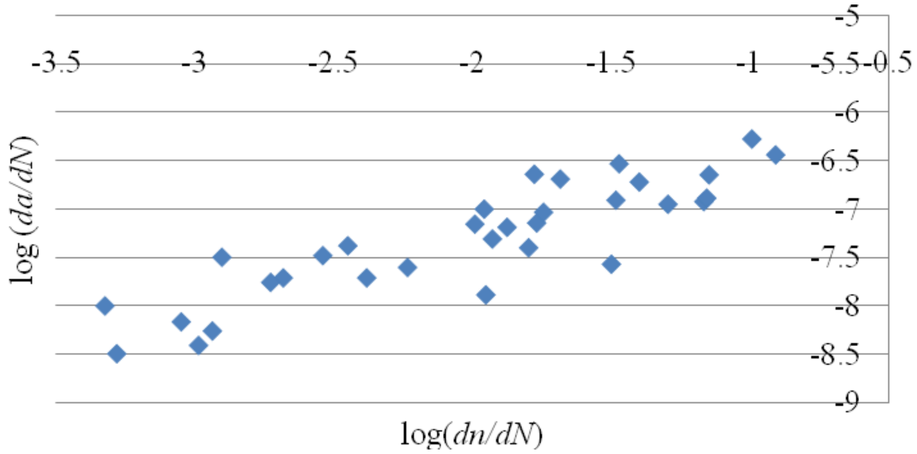

Figure 5: Crack growth rate log(*da/dN*) versus AE count rate log(*dn/dN*).

The relationship between log(*da/dN*) and log(*dn/dN*) had been shown in Figure 5. The AE count rate increased almost linearly with the crack growth rate on logarithmic axes. The results showed that AE parameters such as the AE count rate, log(*dn/dN*) could describe the law of crack growth. Hence, a linear relationship between the crack propagation rate, log(*da/dN*) and AE count rate, log(*dn/dN*) can be drawn as Eq. (5) from Eq. (2) and Eq. (4). Then, it can be expressed after determine the constant value as:

$$log\left(\frac{da}{dN}\right) = 0.738log\left(\frac{dn}{dN}\right) -5.815 \quad (8)$$

CONCLUSION

The fatigue behavior of rail track material was evaluated experimentally using the notched or compact tension specimen. Based on fatigue crack growth test conducted, the Paris Law is given $da/dN = 2.63\text{x}10^{-12}(\Delta K)^{3.29}$. We analyzed acoustic emission signals obtain during fatigue crack growth. The acoustic emission rate and crack growth rate increases linearly with increasing of stress intensity factor. The result also indicated an approximately linear relationship between acoustic emission count rate and stress intensity factor which similar to the Paris Law and can be represented as $dn/dN = 2.63x10^{-7}(\Delta K)^{3.51}$. Theoretical predictions, based on correlation between crack growth rate and acoustic emission count rate were determined and generated an equation of log*(da/dN) = 0.738log(dn/dN) - 5.815.* These methods have significant potential to the inspection, monitoring, assessment and repair of fatigue damaged structures. Thus, further research is required to use other acoustic emission parameters such amplitude, rise time, duration and frequency for monitoring fatigue damage.

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NOMENCLATURE

a	crack length mm
n	number of counts
N	number of cycle cycles
R	load ratio
dn/dN	acoustic emission count rate count.cycle^{-1}
da/dN	crack propagation rate m.cycle^{-1}
AE	acoustic emission
CT	compact tension
W	width mm
C	material constant
M	material constant
B	material constant
p	material constant
ΔK	stress intensity factor range Mpa.√m
K_{th}	stress intensity factor threshold Mpa.√m
S-N	stress – number of cycles