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Detecting Crack Initiation Based on Acoustic Emission

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Acoustic Emission (AE) is a non-destructive testing (NDT) with potential applications for locating and monitoring fatigue cracks during structural health management. In this paper, the AE signal properties for identifying the presence of a small initial crack is assessed to provide the presence of the onset of a potential growing crack. The approach is based on establishing any association between particular features of AE and fatigue crack initiation. Experimental investigation from uniform cyclic loading tests performed on compact tension samples of 7075 aluminium alloys indicated that onset of crack can be identified through a multivariate statistical analysis of AE data. Optical microscopy is used as a measurement tool to size the actual small crack. Result from this testing showed that certain properties of the AE events noticeably change after crack initiation. It was concluded that AE technology can successfully detects crack initiation. The proposed method has significant potential to be used for in-situ monitoring and evaluation of health of structures.

1. Introduction

One of the major concerns in engineering structures is early detection of a growing crack to prevent subsequent damage, predict remaining useful life, schedule maintenance and reduce costly downtime. Acoustic Emission (AE) is a non-destructive testing (NDT) with potential applications for locating and monitoring fatigue cracks during structural health management and prognosis. This paper focuses on in-situ monitoring of structural health specifically detection of small crack growth and crack initiation using AE technology (Keshtgar and Modarres, 2012) The fatigue behavior of small cracks is often very different from large cracks. There is no universally accepted definition of a “small” crack, but most experts consider cracks less than 1mm long (<0.04 in. or <0.001 m) as small (Anderson, 1995). The crack initiation has subjective definitions as well, for example US Navy defines the presence of a crack 0.25 mm in length, as the crack initiation (Iyyer et al., 2007). In this research, small cracks correspond to the crack lengths less than 0.25 mm (250 µm) with low crack growth rates, mostly in threshold region (Region 1) of the fatigue crack growth curve. In this paper the subjectivity of crack initiation will be addressed by determination of the smallest detectable crack size that corresponds to the occurrence of significant AE activities.

A crack propagates at a very low growth rate at the first stage. Therefore, it is very difficult to capture such microscopic crack growths. Of the various test techniques that have been used to record the growth of small fatigue cracks, only a few can provide useful measurements of small-crack growth (Forth et al. 2005). Some measurement methods involve stopping the test to observe and measure the size of small crack. However,, these methods provide post-test information, making real-time monitoring of the small crack behavior impossible (Larson and Allison 1992). It is desirable to not only measure crack length and crack growth rate of small fatigue cracks, but to do so in real time in order to correlate the crack growth rate to AE signal properties.

2. Acoustic Emission Theory

Acoustic Emission may be defined as a transient elastic wave generated by the rapid release of energy within a material (Morton et al. 1973). An AE signal is the electrical signal produced by a sensor in response to this wave (Gong et al. 1992). The characteristics of the AE signal are determined by the mechanism that generated the signal, the means by which it travels through the material, and the sensor

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that transforms the emission into the signal (Beattie, 1983). The most commonly used AE feature for fatigue is the exceedance counts, which is defined as the number of times that the AE signal amplitude exceeds a predefined subjective threshold value (Figure 1). Several attempts have been made to relate other AE parameters such as energy and amplitude to fatigue crack growth properties such as stress intensity factor range (ΔK), maximum stress intensity factor (K_{max}) and crack growth rates (some references include: Lindley et al. 1978, Bassim et al., 1994; Berkovits and Fang 1995, Gerberich and Hartbower 1963, Gong et al. 1998, Roberts and Talebzadeh, 2003; Biancolini et al., 2006; Rabiei et al., 2010). In addition to recording the number of AE counts and correlating this number to the measured damage, it is also helpful to record some certain properties of the AE waveform including "peak amplitude" which is related to the intensity of the source in the material producing an AE, and "Rise Time" which measures the time it takes to reach the peak amplitude of an event (see Figure 1).

3. Experimental

3.1 Material and Specimens

The material used in this study was a 7075-T6 aluminium alloy supplied in the form of compact tension (CT) specimens. The test specimens were manufactured from 3.175 mm (0.125 in.) thick plates. The geometry of the specimens is shown in Figure 2.

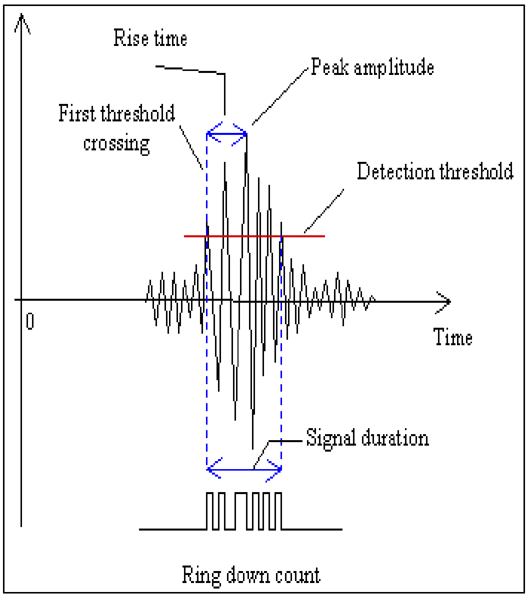

Figure 1. Features of AE signal

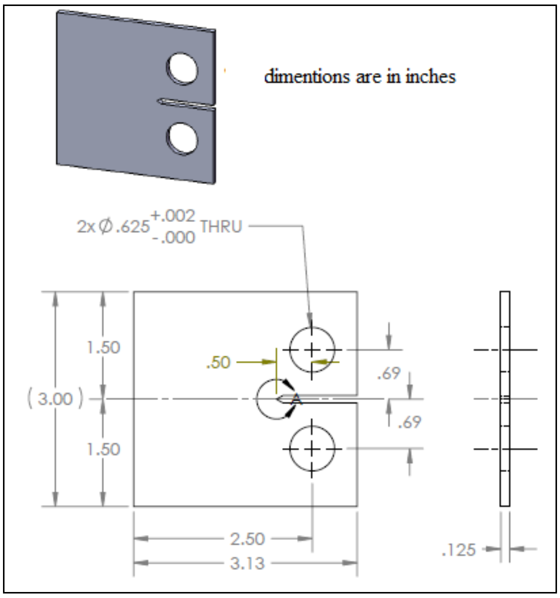

Figure 2. Drawing of CT specimen used in fatigue testing

3.2 System and Test Set Up

An advanced DiSP-4 AE system, supplied by Physical Acoustic Corporation (http:// www.pacndt.com) was used to detect and record the AE signals resulting from the propagation of a crack. This monitoring system consists of four main parts: a single AE sensor to collect the signals and an amplifier to amplify them, a data acquisition module to perform primary filtration and record the signals, and a software module to visualize the data and to perform the feature extraction. The CT specimens were instrumented with the AE sensor and mounted on an MTS 312 uni-axial fatigue-testing machine that applied constant amplitude cyclic loading to conduct the standard fatigue tests. All fatigue experiments were implemented in accordance with ASTM standard (ASTM, 2010) using standard CT specimens under cyclic loading with frequency of 20 Hz and loading ratio of 0.5. The minimum and maximum applied loads were 4.5 kN and 9 kN, respectively. Tests were conducted in laboratory air at ambient temperature. An AE transducer was used to capture AE signals.

The fatigue cracks were monitored by direct measurement using an optical microscope on the front surface. The optical measurement system was composed of several components: a high magnification microscope, a video camera attached to the microscope that tracks the behavior of the crack growth for the duration of the fatigue test, a dual arm fiber optic illuminator, a high resolution monitor, an image processing software with the time-lapse photography capability, and a micro-meter scale to calibrate the photographs taken**.** This measurement system allows detection of small crack lengths, and is sufficient for capturing enough data to correlate observed crack length with the AE signals. Figure 3 shows the optical microscopy test set up used for the small crack experiment.

The assembled optical microscopy unit was focused on the specimen using 50X magnification to observe the specimen notch edge, from which the crack was expected to initiate. A dual arm gooseneck illuminator lighted the target area from both sides, and the camera was used in conjunction with the software to take time-lapse photos of the crack growth. Calibrating the optical system at 50X magnifications using a scale ruler and ImageJ showed that the smallest crack size practically measurable on these tests was on the order of 0.1 mm (100 µm). The crack sizes were monitored until the crack exceeds the length of 0.5 mm. At this point, sufficient small crack data was collected so the test was stopped. A visual record of the crack size is shown in Figure 4.

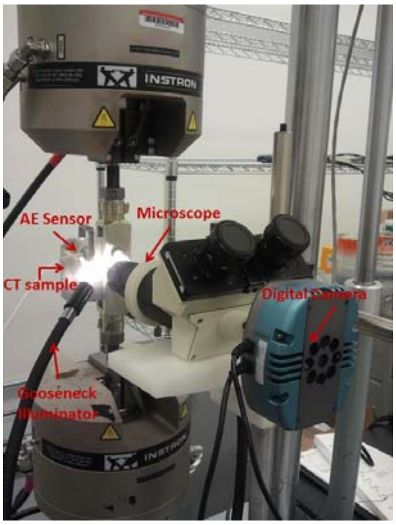

Figure 3. Experimental system set up

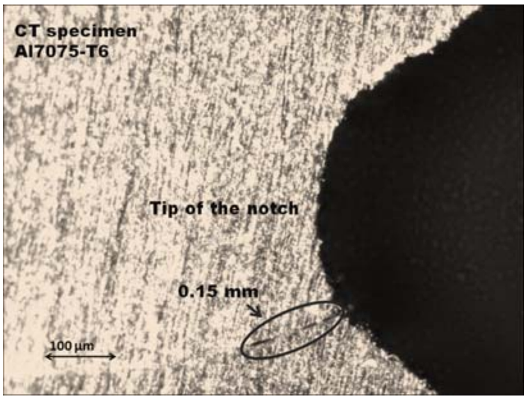

Figure 4. Optical measurement of crack growth

4. AE Fatigue Test Results

In Region 1 (small crack growth area), crack growth per cycle is extremely small and the AE count obtained is about an order of magnitude less than that for large cracks in steady state region (Chaswal et al., 2004); therefore, the AE threshold of 35 dB was used to capture more crack related signals.

4.1 Data Analysis

Signals from the AE sensor were filtered using a band pass filter (200 kHz- 3 MHz) to eliminate emissions from extraneous sources. Acoustic emission data during the loading portion of a cycle were considered related to crack propagation (Robert and Talebzadeh, 2003), and the remaining AE signals related to unloading part of the cycle were not used in the data analysis. The majority of researchers have assumed that only events occurring close to the maximum or peak load are associated directly with crack growth (Rabiei 2011). So, the filtered AE events were separated for different percentages of the applied load range and it was determined that the AE counts occurring within the top 40 % of peak load shows the closest correlation with crack propagation rates.(Keshtgar and Modarres, 2012) The sizes of the pictured cracks were measured using a Java-based image-processing program called ImageJ (Ferreira and Rasband, 2011). Three fatigue specimens were monitored using both acoustic emission and optical microscopy measurement. The results show that cumulative AE counts as well as cumulative AE amplitude have increasing correlation with the measured crack sizes. An example of such a relationship is shown in Figure 5 for experiment CT1. Obviously there is a remarkable similarity between the correlation of AE amplitude and AE counts with the small crack size.

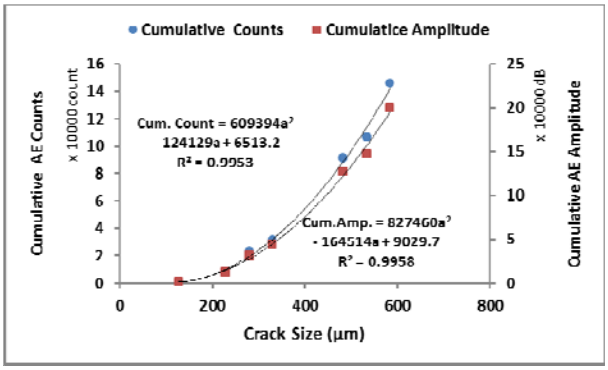

Figure 5. Cumulative AE Count and Amplitude versus Observed Crack Length

4.2 Detection of crack initiation

Acoustic emission-based detection of crack initiation is the ultimate goal of this study. The main idea is that the initiation of fatigue crack corresponds to a sudden appearance of a high peak AE count. These High peak signals might also be due to background noise, micro-crack generation, or plastic deformation. In order to reduce uncertainties and determine the early abrupt jumps in AE events, which correspond to crack initiation, a new averaging index called AE-intensity is proposed to combine multiple features of an AE signal for detecting the onset of cracks (See Eq. 1).

Noise signals have been shown to have relatively higher rise times when compared to AE signals related to the crack. Generally, if the sensor is located near the source, crack related AE signals have a fast rising time, but mechanical noise rarely has such a fast rise time (Miller and Hill 2005). In addition, this study showed that crack-related signals also comprise higher amplitudes as well as higher counts. Therefore, it can be concluded that the signals with lower rise time, higher amplitudes and higher counts correspond to crack growth rather than noise. Estimation of crack initiation time can be implemented by simultaneous evaluation of these AE features. The first appearance of a high amplitude, high count, and low-rise time AE signal corresponds to crack initiation.

$$AE\_Intensity(t) = \sum_{i=1}^{3}\left(w_1 C(t) + w_2 A(t) + \frac{w_3}{R(t)} \right) \qquad (1)$$

where *C (t)* is the normalized number of counts at a specific time *t*, *A (t)* indicates the normalized amplitude of the signal and *R (t)* is the normalized rise time of the signal at time *t*. Weights were subjectively selected as:

$$w_1, w_2 = 1/3 \quad , \quad w_3 = -1/3 \qquad (2)$$

Post processing of the data recorded revealed that no AE event believed to be caused by crack initiation during the first 18,700 cycles of monitoring the tests, even though some AE signals were recorded due to background noise. For experiment CT1 the first jump in AE intensity (sudden increase of 62 %) was detected at approximately 18700 Cycles, which is an indication that crack initiation was taking place. Similar observation achieved for other tests. The numbers of cycles for crack initiation were 19,400 and 20620 for experiment CT2 and CT3, respectively and the jumps observed in AE intensity were more than 50 % sudden increase (60.5 % for CT2 and 59 % for CT3) Cumulative AE intensity was calculated for the time of crack initiation and for the entire crack growth duration. A linear correlation was observed between the cumulative AE intensity and crack sizes. As it can be seen in Figure 6, linear correlation between AE-Intensity and small crack growth exists in the entire crack length range. The slopes of the lines from those three experiments are apparently similar to within ± 10 %. The length of initial crack at the estimated initiation time could be quantified using the linear relationship between the cumulative AE intensity and crack length. Back extrapolation method was used to estimate the actual crack initiation length at the time of observation of the first jump in AE-Intensity event for each experiment. The results are summarized in Table 1.

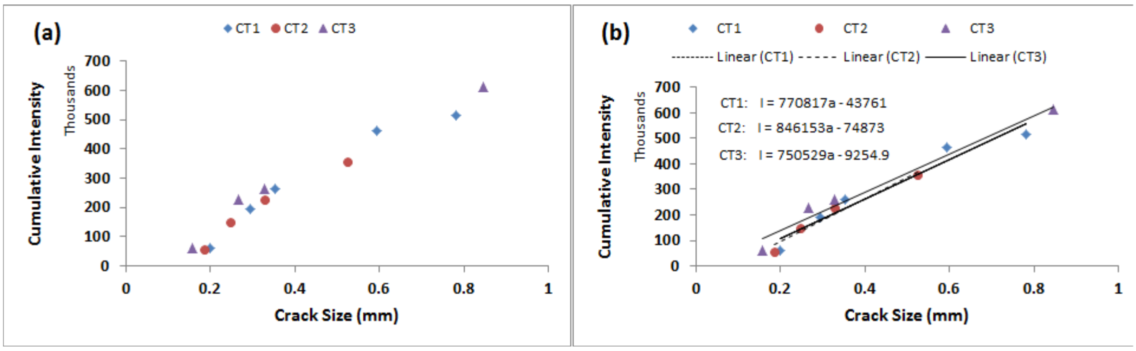

Figure 6. Correlation between AE intensity and crack size for different experiments (a) observed correlation (b) fitted linear lines

Table 1: Estimated Crack Initiation Lengths

Experiment	t_0 (sec.)	I_{cum} (at t_0)	a_0 (μm)
CT1	935	37.2	56.8
CT2	970	37.8	88.5
CT3	1031	28.48	12.3

5. Conclusions

A method for detecting crack initiation during high cycle fatigue tests was demonstrated using AE monitoring. Filtering techniques were employed during the recording and interpreting of the AE data. An intensity index for AE events was proposed to reduce the noise and distinguish the AE signals from initiated crack. Acoustic emission intensity encompasses the total value of weighted features including count, amplitude and rise time. It was discussed that the first detected jump (more than 50% sudden increase) in intensity of AE signals having a relatively fast rise time and high amplitude, as well as high-count numbers corresponds to the crack initiation. The small crack lengths were measured experimentally using optical microscopy in conjunction with image processing methods. The results proved linear relationships between AE intensity and small crack growth. The AE intensity monitoring results were in a good agreement with different experiments. The estimated crack initiation length that corresponds to the first jump in intensity of AE event was obtained by extrapolation of the fitted linear model. The proposed method is one example of weighting features for intensity calculation; other options are being investigated to find the most consistent detection results. Additional experimental data would be necessary to establish a probabilistic estimate of the crack length probability density function at the time of crack initiation.

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