International Journal of Fatigue 81 (2015) 117–127

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

Effects of loading and sample geometry on acoustic emission generation during fatigue crack growth: Implications for structural health monitoring

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ARTICLE INFO

Article history:
Received 10 February 2015
Received in revised form 20 July 2015
Accepted 27 July 2015
Available online 5 August 2015

Keywords:
Fatigue crack
Acoustic emission
Probability of detection
Crack closure

ABSTRACT

The reliability of traditional non-destructive methods for crack detection is well understood and characterised using Probability of Detection (POD) curves. Structural Health Monitoring (SHM) techniques in contrast remain largely unquantified. The performance of the Acoustic Emission (AE) technique for damage detection and location in potential SHM applications is underpinned by the intensity of AE signal generation from the damage site. In this paper, factors influencing the rates of emission of Acoustic Emission (AE) signals from propagating fatigue cracks were investigated. Fatigue cracks were grown in specimens made from 2014 T6 aluminium sheet while observing the effects of changes in crack length, loading spectrum and sample geometry on rates of acoustic emission. Significant variation was found in the rates of AE signal generation during crack progression from initiation to final failure with a number of distinct phases identified in that progression implying different failure mechanisms operating at particular stages in the failure process. A new 'probability of hit' method for quantifying crack detecting capability using AE is also presented.

1. Introduction

Structural Health Monitoring (SHM) techniques are developed as an alternative to Non Destructive Testing (NDT) methods for inspection of aircraft structures. These techniques are potentially capable of performing continuous or on-demand diagnosis and damage detection via permanently installed sensors. The advantages are increased availability and reduced maintenance costs. The Acoustic Emission (AE) technique is one of the SHM tools capable of fatigue crack detection in metallic structures via guided ultrasonic waves generated from damage sites such as fatigue cracks. Identification of crack location can be performed using measurements of the time difference of arrival of AE signals at different sensors in an array [1].

The performance of the AE technique for damage location and detection is influenced by multiple parameters involved in the sequence from sound generation through detection to signal processing [2]. These influences can be classified into four categories, namely: AE signal generation [2,3], AE signal propagation [4], AE signal detection [5,6] and data processing [2]. In this paper, attention is focused on the signal generation stage of the AE detection process.

AE generation from fatigue cracks can originate from different sources which are classified as either primary or secondary [7]. Primary AE sources are generally associated with fracture mechanisms occurring around the crack tip which includes crack extension [8–10] and deformation of plastic zone around the crack tip which results in local failure of second phase particles [10–12]. Secondary AE sources on the other hand are related to crack closure processes which results in fretting of crack surfaces [7,9,13].

Scruby et al. [9] conducted a study to characterise AE generated from crack extension during fatigue crack growth in 7010 aluminium alloy. It was concluded that crack extension is not the dominant source of AE from fatigue crack growth since ductile tearing of the material occurs in every loading cycle and the rate of recorded AE was much lower, an average of about 1 AE signal in 20 cycles.

Several studies have been conducted to investigate sources of AE during plastic deformation in aluminium alloys [8,11,12,14,15]. McBride et al. [11] and Lugo et al. [14] similarly presented results that showed generation of AE from fatigue crack to be dependent on the existence and size of inclusions in aluminium alloys. McBride et al. [11] observed the influence of material strength on the fracture of inclusions and the consequent

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http://dx.doi.org/10.1016/j.ijfatigue.2015.07.024
0142-1123/

generation of AE and a strong correlation was made between the number of fractured inclusion and the number of AE signals recorded.

Fretting of crack surfaces may also be expected during fatigue crack growth which could be dependent on crack closure. AE signals generated from this source are generally considered to be of the continuous type [11,16]. Moorthy et al. [10] noted that AE signals can be generated from plasticity-induced closure, which is more prominent in plane stress, as well as asperity or roughness-induced closure, which results from a mismatch between crack surfaces as a function of the coarse microstructure of a material. This phenomenon is also known to be dependent on the level of constraint on in-plane bending [17].

Few studies have been conducted to quantitatively characterise AE generation during fatigue crack growth as a function of loading conditions. Han et al. [18] using single-edge notch samples of steel and welded steel investigated the trends in AE emissions caused by increased peak load at a stress ratio of 0.1. The results showed distinct stages in normalised cumulative AE counts (number of times AE signals cross a specified amplitude threshold value) over periods of cumulative fatigue load, associated with crack initiation, growth and final failure. An increase in normalised cumulative AE counts with increased peak load was also observed in the case of the welded steel sample. It should be noted however that the actual rate of AE generation could not be directly inferred from AE counts data because the count rate per signal varied throughout crack growth.

Daniel et al. [19] also performed a similar study to characterise AE generation in aluminium and steel coupons as a function of phase in the fatigue loading cycle. Several distinct groups of AE signals were identified and attributed to plasticity, crack closure and the transition from plain strain to plain stress during crack propagation.

The viability of the AE technique in detecting and locating damage such as a fatigue crack in potential SHM applications is completely dependent on the AE signals being generated from the damage site, such that they may be distinguished from background noise. The circumstances under which these AE signals could be generated may vary widely depending on loading conditions and component geometry. Based on the above reported observations, and given the variety of potential sources of AE it may be expected that use of fixed threshold methods may limit the successful detection of cracks.

The reliability of currently employed NDT inspection methods is characterised using Probability of Detection (POD) curves derived using standard procedures [20]. In contrast however, no equivalent, standardised approaches have yet been developed for SHM techniques and their reliability and performance limitations are still largely unquantified. If AE is to be relied upon as a form of SHM to indicate the presence and growth of damage such as fatigue cracks in metals, the relationships between structural geometry and loading on the detected signals from sensors must be better characterised.

In this paper, a series of controlled experiments were conducted to investigate the influence of loading and sample geometry on AE generation during fatigue crack growth. The effects of stress ratio and stress range were explored as well as whether the fatigue crack was initiated from a sample with Single Edge or Middle-crack Tension notch. A new 'probability of hit' metric is introduced as a basis for quantifying the crack detection capability of the AE technique.

2. Experiments

A set of 12 test specimens were made from 2 mm thick 2014 T6 aluminium alloy sheet comprising 11 Single Edge Notch (SEN) and 1 Mid-crack Tension (MT) specimens. For all specimens the dimensions were 530 mm by 250 mm with the longest sides parallel to the rolling direction. The SEN specimens had a 10 mm notch machined at the midpoint into one of the longest edges and the MT specimen had a 20 mm central notch. The mechanical properties of the test material are shown in Tables 1.

For the MT samples the expression given in ASTM E-647 and shown in Eq. (1) was used to determine values of stress intensity factor range ΔK for all crack lengths.

$$\Delta K = \frac{\Delta P}{B}\sqrt{\frac{\pi\alpha}{2W}\sec\frac{\pi\alpha}{2}} \quad (1)$$

where ΔP – the cyclic load range, B – sample thickness, W – total sample width and $\alpha = 2a/W$, where a is the crack length.

A two-dimensional finite element analysis was conducted using the contour integral function in ABAQUS to obtain values of the stress intensity factor for all crack lengths.

Fig. 1 shows values of β for SEN and MT samples plotted against crack length. As the MT sample has a central crack with two tips, half crack length is plotted. The β values for the two geometries are very similar until crack lengths of 100 mm are exceeded when the M(T) crack tips approach the sample edge and β increases significantly.

The specimens were fatigued on a servo hydraulic test machine under constant amplitude loading with nominal frequency of 2 Hz and stress ratio (*min.stress*/*max.stress*) of 0.1 and 0.5. Fig. 2 illustrates a schematic of the experimental setup.

The surface of the sample was polished and scribed at 1 mm intervals to provide an accurate visual indication of the crack tip position. A video camera system was used to monitor crack lengths during the fatigue tests, acquiring image frames with a timestamp at a specified rate. The time stamp allowed each image to be correlated with cycle number and with acoustic emission signals. After the test was over the crack length versus cycles data were processed into crack growth rates using the secant method prescribed in ASTM E 647-00.

Table 2 shows a summary of test conditions and sample geometry. Tests 1–7 were performed on SEN samples with a stress range of 52 MPa. The stress intensity range (ΔK) of the newly initiated crack was 10.4 MPa$\sqrt{m}$ for the SEN samples. The effects of stress range, stress ratio and geometry on AE signal generation were observed in the additional tests, performed on specimens 8–12 with reduced stress range of 27 MPa and increased stress ratio of 0.5. The mid-crack tension sample was sample 12.

A multi-channel Physical Acoustics AE system was used to monitor AE signals using broadband piezoelectric sensors with sampling rate of 2 MS/s. Pre-amplifier gain for each channel was set at 40 dB and the AE signal detection threshold was set at 45 dB. The load output of the test machine was monitored via a ±10 V analogue input.

Spurious AE signals generated from the test machine grips during cyclic loading were excluded by implementing a spatial filter: signals originating from outside the sensor array were rejected based on the Time Difference of Arrival (TDOA) measurements obtained from the detected signals. The filtering range was set between 28 μs and −23 μs which created an active sensing region between 172 mm and 320 mm on the horizontal axis. This set-up consisted of a pair of sensors 200 mm apart as illustrated in Fig. 3. It is capable of performing 1D AE event location along the

Table 1
Mechanical properties of 2014 T6 aluminium material.

	Yield strength (MPa)	Ultimate tensile strength (MPa)
Mean	439	492