

Detection of Cracking in Mild Steel Fatigue Specimens Using Acoustic Emission and Digital Image Correlation

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Abstract. The aim of this investigation was to identify sources of AE in mild steel fatigue specimens and relate them to damage mechanisms. Digital Image Correlation (DIC), a full-field strain measurement technique, was used to validate the findings. This paper describes in detail the results of a ‘dog bone’ style specimen undergoing uni-axial fatigue loading. This test forms part of a much larger programme designed to develop an AE monitoring system to identify damage initiation and growth from background noise in fatigue testing of automotive steels subjected to corrosion.

Crack growth was monitored in the test using two AE sensors and, to allow a comparison with the detected and located signals, DIC images were captured periodically at peak loads. As part of the initial analysis located signals were compared with areas of high deformation and crack growth as identified by the DIC system. Results demonstrated that it is possible to distinguish the different AE signals originating from various possible failure mechanisms such as Plastic deformation, delamination of DIC paint and crack initiation and propagation. This might be utilized for an effective and powerful approach to monitor multiple failure mechanisms; this has significant applications in automotive chassis testing.

Introduction

One of the main requirements in the design of many mechanical components is the ability to resist a large number of stress cycles under service loads. Fatigue life can be defined as the number of cycles involved in the growth of a crack from dimensions of the order of material grain size up to final fracture of the component [1]. This definition highlights that defects or inhomogeneities (manufacturing defects, inclusions or pits), which are larger than the material’s inherent micro-structural dimensions, are hugely detrimental to fatigue life and strength. In light of this, the effect of fatigue behaviour on pre-corroded mild steel was studied and plastic deformation, crack initiation and growth were identified using Acoustic Emission (AE) and Digital Image Correlation (DIC).

AE technology has been widely developed over four decades as a non-destructive evaluation technique and as a useful tool for materials research. It is a highly sensitive technique for detecting active microscopic events in a material, as well as crack initiation and propagation [2, 3]. DIC was used to determine the onset of cracking for comparison with the detected AE. Thus it was used to support the understanding of the detected AE



signals. The two techniques were used in order to neutralize their weaknesses [4]. Few previous studies have been conducted using the combination of DIC and AE under fatigue loading. This combination of techniques has been used previously by Pullin et al [5, 6] under fatigue loading; the first of these two studies was carried out on four point bending fatigue of aerospace steel and the second one was performed on detection of cracking in gear teeth. Other researchers have used the combination of AE and DIC but under static load. Kovac *et al.* 2010 used both these techniques to monitor AISI 304 stainless steel specimens subject to constant load and exposed to an aqueous sodium thiosulphate solution [7]. Aggelis *et al.* used both these techniques to monitor bending failure of concrete beams reinforced by external layers of different composite materials [4]. Pullin et al [5, 6] pointed out that the method of crack monitoring, with AE, had to be non-contact so as not to produce frictional sources of AE in the crack region.

This study forms part of a much larger ongoing programme designed to develop a monitoring system for fatigue tests to identify damage initiation and growth against background noise. This programme investigates automotive steel applications (specifically in chassis), where crack initiation is considered a significant characteristic in automotive chassis design, particularly with the trend towards weight reduction and the increasing use of high strength steels. Therefore it is important to identify the crack initiation location and mechanism. In this study AE was used to detect the onset of damage in a fatigue dog-bone style specimen undergoing axial fatigue loading and the results were correlated with damage mechanisms.

1. Experimental Procedure

1.1 Specimen preparation

The specimens were subjected to fatigue load ranging from 41 % to 85 % of the ultimate tensile strength (423.7 MPa), with a stress (R) ratio of 0.1 and a frequency of 5Hz. Figure 1 shows the fatigue dog-bone specimens which were manufactured from 3 mm thick, mild steel plate (0.2% proof stress 275 MPa, ultimate strength 423.7 MPa and elongation 36% based on three coupon tests). Part of the specimens were subjected to alternating spraying of 5 % NaCl solution according to a corrosion procedure as explained in SAEJ2332 [8] .

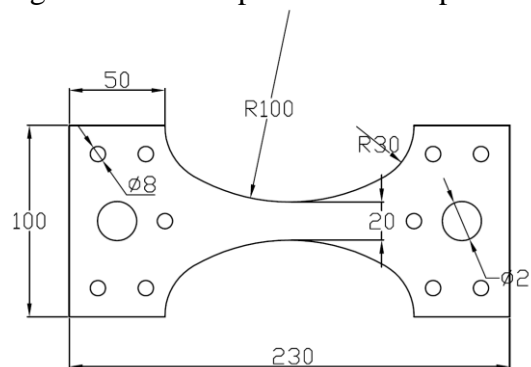


Fig.1. Details of fatigue specimen geometry (dimensions in mm)

1.2 Acoustic Emission and Digital image correlation preparation

A combination of AE and DIC was used to monitor the fatigue crack growth during the fatigue tests. Test specimens were instrumented with two Mistras Group Limited (MGL) Nano 30 sensors, the sensors being held in position with silicone grease which was also

used as an acoustic couplant. Installed sensor sensitivity was evaluated using the pencil lead fracture technique. The response to the Hsu-Nielsen source of both sensors, in all tests, was above 97 dB [9]. In order to eliminate experimental noise, a threshold of 45 dB was used.

The test was stopped at 1000 cycle intervals, peak load applied and DIC images captured as shown in the load history shown in Figure 2a [6, 10]. Figure 2b schematically shows the fatigue specimen is held on pinned joints in a Losenhausen servo-hydraulic testing machine (maximum force 100kN) with an MTS FlexTest controller and equipped with AE and DIC equipment in order to track the crack growth during fatigue test. The relative movement of two pixel subsets for either side of the crack was used to provide a crack mouth opening displacement (CMOD) measurement in order to validate and support the understanding of the collected AE data. Using DIC offers significant advantages over foil crack gauges and traditional crack mouth opening displacement gauges. Both these traditional methods can introduce acoustic emission sources into the experiment either through glue cracking in foil gauges or frictional noises from the CMOD gauge contact point with the specimen. DIC images were collected every 1000 cycles using a Dantec Dynamics Q-400 system which was triggered from the MTS controller while holding briefly at maximum load.

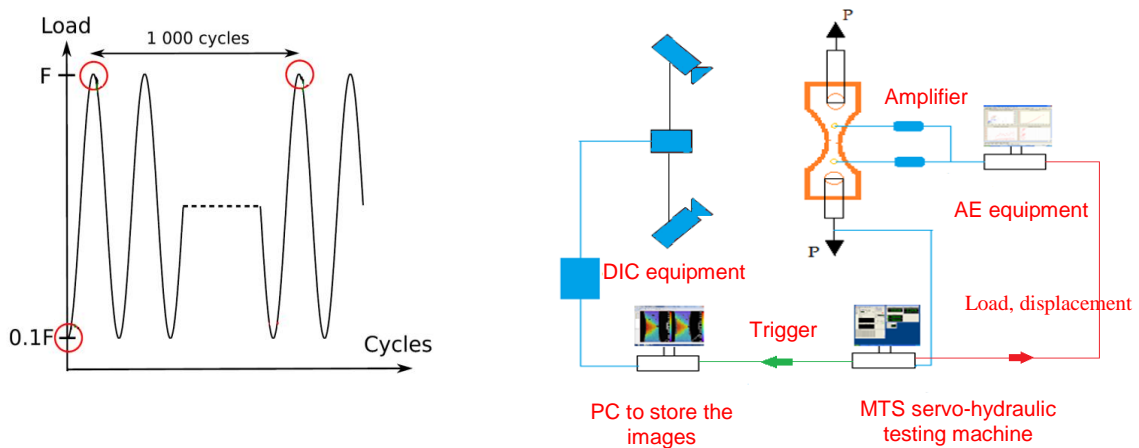


Fig. 2. (a) DIC Image capture during the load history, (b) schematic diagram of fatigue test

2. Results and Discussion

AE is a highly sensitive technique; it acquires AE information from both real cracks and noise. Eventually, the different types of noises hamper the reliability and accuracy of AE analysis [11, 12]. To remove AE noise data related to surface rubbing at the pins, environmental noise and other unknown sources generated outside the tested materials, all data files were filtered according to spatial position for a wide region. This region included the fatigue crack growth and crack closure (rubbing of the crack faces), but also plastic deformation of the material around the crack tip and elsewhere.

Cumulative counts and cumulative absolute energy are two parameters that are used to develop plots that correlate to the fatigue crack growth process with time [13]. In the present study these AE parameters were compared with the DIC results (CMOD measurement) and plotted against number of cycles (N) under various stress levels.

Analysis was performed and is presented in detail for a fatigue test with a peak stress of 320MPa (Case I) for specimen previously subjected to 25 days of corrosion. Figure 3 shows the digital image correlation-derived CMOD measurement and AE data

recorded during the fatigue test. It can be seen from the plot that the initial increase in acoustic activity coincides with an increase in crack mouth opening, suggesting that the AE came from the crack.

It worth mentioning that the plastic deformation effect can take place throughout the fatigue process, especially in the early stages of the test, and it generated significant AE. It was obvious in this test under high load (Case I), however it also occurred under lower load [14].

Here it was observed that the plastic deformation effect was accompanied by pronounced AE activity due to the dislocation glide and deformation twinning [15, 16]; this is clear from the significant AE activity at the onset of the test which is represented by group A (dashed line rectangle) in Figure 3b. It can be seen from this figure that those signals which are emitted from plastic deformation had an amplitude of around 45-50 dB, which agrees with the findings of Barsoum [13].

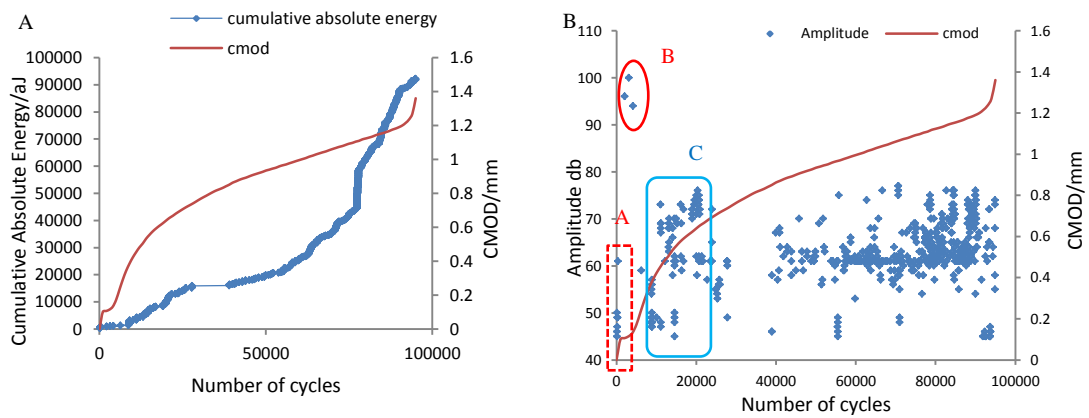


Fig. 3. (a) Cumulative absolute energy (b) Amplitude on primary axis and CMOD on secondary axis vs number of cycles for corroded specimen under 320MPa maximum stress

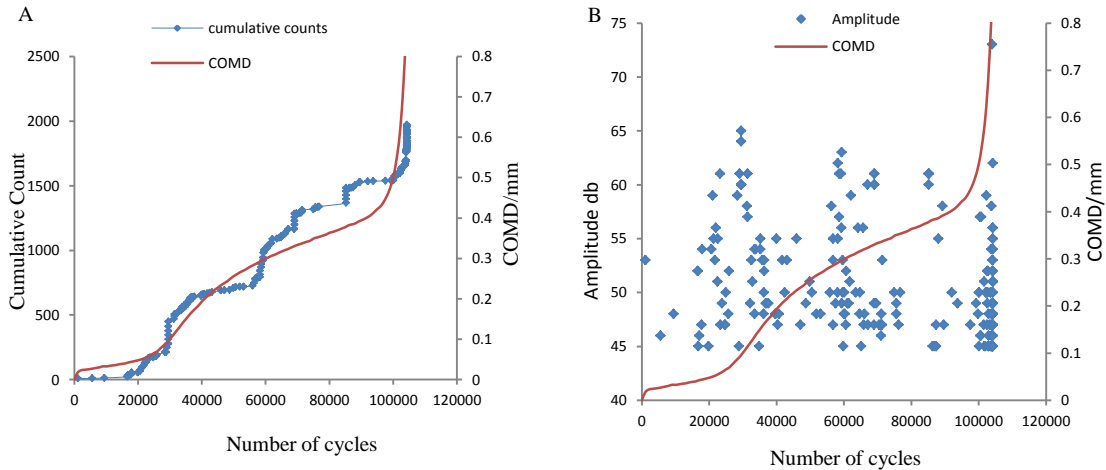


Fig. 4. (a) Cumulative counts (b) Amplitude on primary axis and COMD on secondary axis vs number of cycles for un-corroded specimen under 320MPa maximum stress

Figure 4 shows the test results for an uncorroded specimen (Case II) under similar loading conditions to Case I. In this test the specimen was reused for a second time. Firstly this specimen was loaded under 211 MPa for around 5.6 million cycles then re-loaded at 320MPa until failure at 104247 cycles. It can be seen from Figure 4(b) that there was no significant AE activity at early stages of the test when compared to Case I. The possible

reason for this is that plastic deformation happened in the first loading at a lower load; from this it can be seen that both DIC and AE can detect plastic deformation.

In order to analyse Case I in more detail, considering Figure 3(b), it may be seen that there was a group of signals (group B) having high amplitudes above 94dB. Consideration of both AE and DIC data allows these signals to be identified as resulting from the mechanism of brittle fracture or delamination of corrosion products from the underlying substrate material. Consideration of the location of signals, identified by the time of arrival method using commercial software (AEwin), identifies these signals as being generated by a source at an “X” location (along the test specimen’s reduced section) of 0.01-0.02m, as shown in Figure 5(a). Inspection of the corresponding DIC image in Figure 5(b) shows a high level of out-of-plane displacement at this location, highlighted in Figure 5(b). The out of plane displacement at this location was compared to that at surrounding points (Figure 6) and shown to have a higher level, increasing with loading cycle, indicating the gradual flaking of corrosion product. Post-test visual inspection of the specimen confirmed the presence of flaking corrosion product at this location.

Again Figure 3b shows a slight increase in AE activity around 8k cycles which is represented by group C (rounded rectangle). This is not obvious in Figure 3(b); however an increase can be seen in the enlarged view shown in Figure 7(a). This increase in AE activity was probably generated from two mechanisms. The first one is the crack initiation and the second one is most likely the noise due to delamination of DIC paint which is rubbing with specimen surfaces around the crack path, so that might be a limitation of this technique. Figure 7(b) shows out of plane displacement which reveals DIC paint was flaked due to the crack initiation underneath it, potentially producing high levels of AE activity. There was another significant increase in AE activity around 16k cycles accompanied by a similar increase in DIC pattern, Figure 7(c). This increase may have resulted from crack extension and other signals related to these mechanisms such as plastic opening at the crack tip, plastic zone extension and crack advance [13, 17]. This increase demonstrates that the crack has started and was consistent between both techniques. This increase was largely caused by crack growth) as opposed to plastic deformation away from the crack tip, observations which are consistent with those of Pullin et al [5].

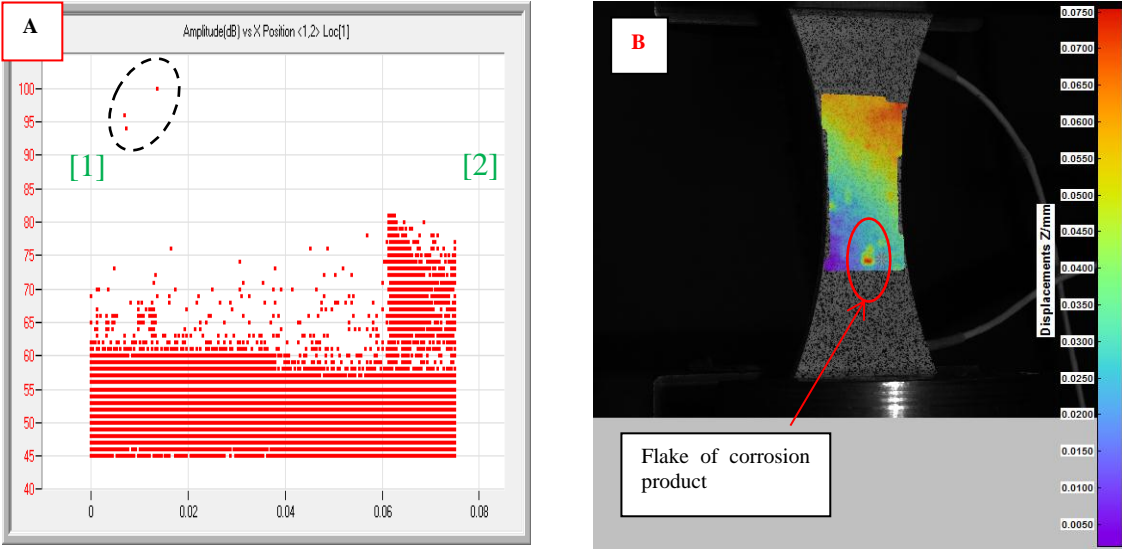


Fig. 5. reveals the flake in the corrosion product by DIC and AE methods

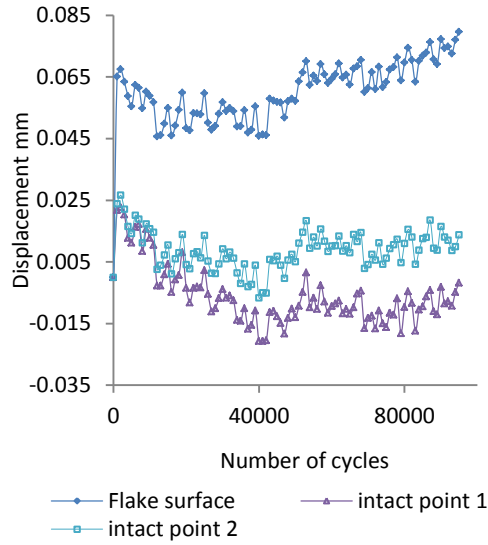


Fig. 6. Out of plane displacement for intact and flake surface

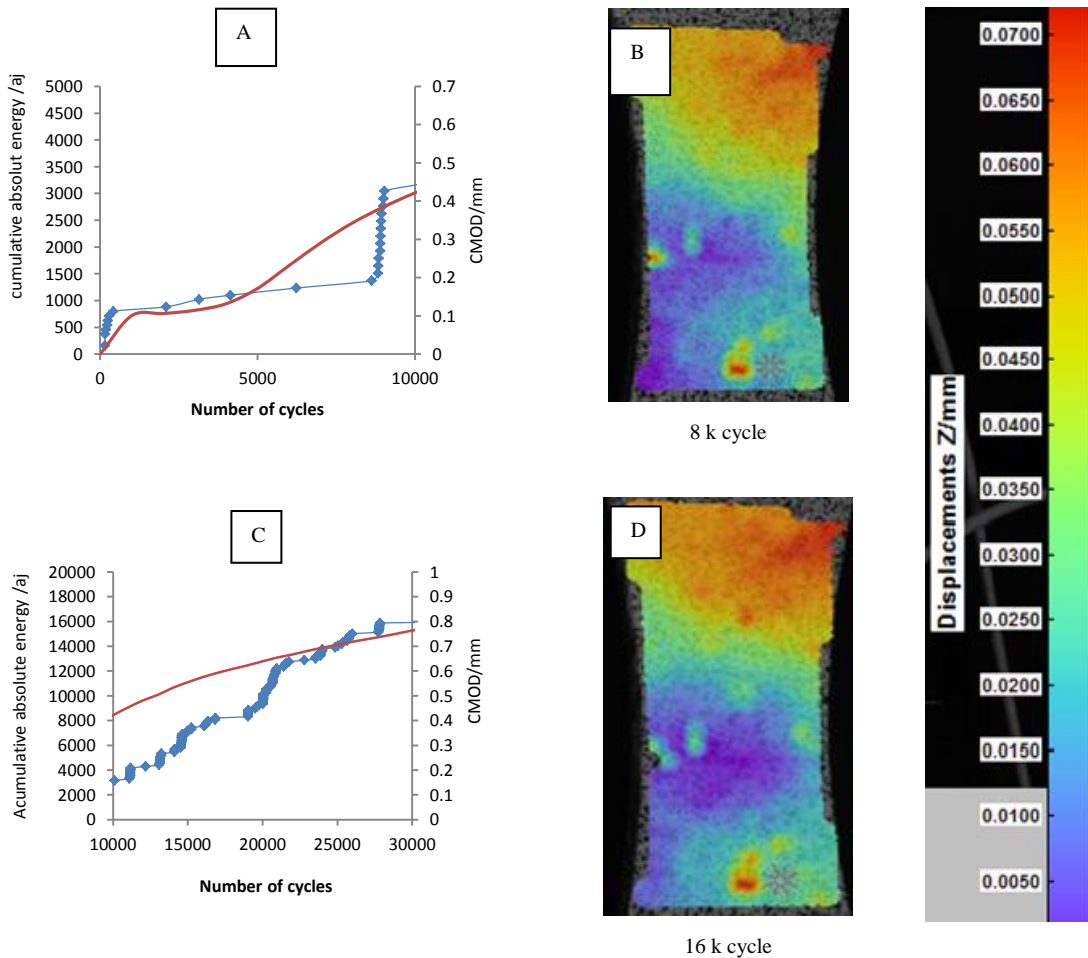


Fig. 7. Focused view of Figure 3 and corresponding DIC images

The observations of AE for Cases I and II show slightly different characteristics. In Case I there was an increase in AE activity at an early stage of the test; this was attributed to plastic deformation. The signals generated from crack initiation were mixed with a large number of signals generated by the damaged DIC paint on the specimen surface around the

crack path which are represented by group C in Figure 3(b). These signals were followed by a reduction in the AE activity for a stable prolonged period of 23-40 k cycles. The most likely reason for this reduction in the AE activity is that the DIC paint failed or peeled off as shown from DIC image Figure 7 (d); this eventually lead to stopping of the rubbing. Additionally, it can be noticed that crack propagation started early in case I at around 8k cycles whilst in case II it started at around 20 k cycles because the specimen in case I was corroded thus having surface pitting and increased roughness which generates stress concentration sites.

Conclusions

This study revealed and identified the mechanisms that occurred during crack growth. Fatigue tests were monitored using the AE technique in order to detect fatigue damage in mild steel and correlate the results. The results demonstrate the capabilities of AE for detecting fatigue fractures; it can also be argued that it is possible to distinguish the different AE signals originating from various possible failure mechanisms. Plastic deformation and delamination of DIC paint as well as crack initiation and propagation have been identified.

DIC provided a clear depiction of the surface strain field and its transient changes according to stress redistribution which occurs as the crack propagates. It is a useful method for monitoring the whole area of interest and it is not limited to a specific region, therefore any damage or microcracks can be detected and recognized. DIC was used to support the understanding of the detected AE signals. Complementary use of DIC and AE helps to minimize the assumptions in the interpretation of the AE trends in relation to the responsible damage mechanisms by revealing the fluctuation of the surface strain fields.

In the study, it was possible to detect crack initiation and distinguish it from various other mechanisms, where this might be utilized for an effective and powerful approach to monitor multiple failure mechanisms; this has significant applications in automotive chassis testing.

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