Analysis of Acoustic Emission Waveforms from Fatigue Cracks

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ABSTRACT
Acoustic emission (AE) monitoring technique is a well-known approach in the field of NDE/SHM. AE monitoring from the defect formation and failure in the materials were well studied by the researchers. However, conventional AE monitoring techniques are predominantly based on statistical analysis. In this study we focus on understanding the AE waveforms from the fatigue crack growth using physics based approach. The growth of the fatigue crack causes the acoustic emission in the material that propagates in the structure. One of the main challenges of this approach is to develop the physics based understanding of the AE source itself. The acoustic emission happens not only from the crack growth but also from the interaction of the crack lips during fatigue loading of the materials. As the waveforms are generated from the AE event, they propagate and create local vibration modes along the crack faces. Fatigue experiments were performed to generate the fatigue cracks. Several test specimens were used in the fatigue experiments and corresponding AE waveforms were captured. The AE waveforms were analyzed and distinguished into different groups based on the similar nature on both time domain and frequency domain. The experimental results are explained based on the physical observation of the specimen.

Keywords: NDE, SHM, Acoustic Emission, Fatigue Crack, Physics based modeling, Finite Element Analysis

1. INTRODUCTION
The acoustic emission (AE) technique to detect structural damage has been used for many years, however, the actual physics of the acoustic emission due to fatigue cracks is yet to be analyzed [1]–[5]. The AE analysis is a passive detection technique of Structural Health Monitoring (SHM) and Nondestructive Evaluation (NDE) [6]–[8]. Both active [9]–[11] and passive [5] detection methods are utilized to detect the fatigue cracks in aluminum alloy. However, most of them focused on the ex-situ fatigue crack analysis.

The AE based methods have been applied in many materials such as isotropic, anisotropic, composite and concrete materials [12]–[16]. Source localization, as well as source characterization, have been performed using AE hit analysis [17]–[20]. Crack growths in notched specimen were analyzed using AE hit data-driven approach [21]. However, many methods of AE analyses mainly focused on the first arrival time and peaks of the AE waves. Finite element analysis and some analytical works have been performed to understand the mechanism of AE source [13][22]. The various parameters of an AE waveform were calculated that included average frequency, maximum amplitude, time of flight, duration, counts, and hits. However, the examination of few AE waves provided very limited useful information of the AE from a crack growth. In fact, the complex nature of the AE wave generation, propagation, interaction with the structural features made it much difficult to analyze individual AE waveforms. Most of the researchers focused on statistics based method in spite of physics of materials based approach.

In this paper we attempted to explain the underlying physics of different types of AE waveform ID. Fatigue experiments were designed to generate the AE waveforms. Several test coupons were experimented under fatigue loading and the corresponding AE signals are recorded. Physics based approach were used to analyze the individual AE waveform. The AE waveforms were classified into three major groups and the corresponding physical phenomena were explained. 3-D finite element harmonic analysis was applied to predict the interaction between the crack and AE waveforms at wideband of frequencies. Laser Doppler vibrometry experiments were conducted on an aluminum plate with manufactured crack to verify the crack resonance phenomena. The preliminary results suggest that the crack resonance phenomena could be used to extract geometric information fatigue crack from the AE waveforms.

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2. FATIGUE EXPERIMENTAL SETUP

The fatigue experiments were designed to capture the real time AE signals. Aircraft grade aluminum 2024 T3 test coupons were used. Two specimens were used for this purpose. One specimen is relatively thinner (38 mm wide) and another is relatively wider (100 mm wide). The first one undergoes the fatigue cycle until it breaks but the second one we wanted not to break and grew the crack longer than the first one. Both specimens are 300 mm long and 1 mm thick. A small (1 mm diameter) hole is created at the center of the specimen to initiate the crack growth. It is important to minimize the boundary reflections to extract the AE signal that are related to fatigue crack. Thus an absorbing clay boundary around the crack was used. The fatigue loading level was selected based on the yield limit of the materials. The MTS 793 mechanical testing machine was used to apply the fatigue loading in the specimen. The highest load level was 65% of the yield strength of aluminum 2024 T3 and the lowest load level was 6.5% of the yield strength. The fatigue experiments are conducted into two stages of loading rate. At the beginning the loading rate was relatively higher (4 Hz). At this stage the coupons undergo internal changes, crack initiation, and then starts to crack grow. While the crack is growing we wanted more control on capturing the AE events and thus decrease the loading rate to 0.25 Hz.

The piezoelectric AE sensor (PWAS) was installed close to the initial drilled hole as shown in Figure 1(b). The reasons for such proximity of the PWAS were to capture the low amplitude crack resonances of the AE waveforms. The surface strains near the crack region are relatively lower than that in the far away from the cracks. This ensures the firm bonding of the piezoelectric sensor in the specimen.

Since the AE signals are low in amplitude the preamplifiers were used in between the sensor and the AE hardware. The preamplifier also filtered the very low frequency vibration signals. Those vibration signals are not related to the AE signals and are persistently present there originated from the machine and other sources. The digital AE system from the physical acoustics was used to detect the AE signals.

![Figure 1: (a) Fatigue experimental set up, (b) PWAS transducer mounted on the specimen (c) AE measuring instruments](image)

3. MICROSCOPIC ANALYSIS OF FATIGUE CRACKS

The crack surfaces of the relatively thinner specimen are presented in this section. The crack surfaces was then monitored under a high magnification microscope. An initial crack followed by a plastic deformation was formed at the end of the first stage. The specimen was examined under the microscope to clearly observe any microscopic change around the hole. No significant change was observed until 8000 fatigue cycles. At this stage, no significant acoustic emission was observed. At 8000 cycles, plastic deformation was noticed on the both side of the hole that seemed like a dent by the naked eye. The microscopic image was shown in Figure 2. Both plastic deformations were almost same lengths that were marked by the two red ellipses as shown in Figure 2. The left side plastic deformation was horizontal while the right side plastic deformation was little inclined to the horizontal line. This may be because of the manufacturing imperfection of maintaining homogeneity in the material. The fatigue loading was continued after the...
examination under the microscope. At 8200 cycles, the plastic deformations turned into initial cracks marked by two red ellipses as shown in Figure 2.

Once the crack was initiated at 8200 cycles, the AE signals were triggered significantly. Then, the fatigue loading was switched to the second stage. The second stage loading facilitated better control of the AE signals capturing with crack growth. The crack grew as the fatigue cycles continued. The microscopic image of the crack growth at three fatigue cycles (8200, 8700, 9200 cycles) was shown in Figure 3. The fatigue crack grew 300 µm in one side of the hole as the specimen underwent 500 fatigue cycles starting from 8200 cycles. In the next 500 fatigue cycles, the crack grew 360 µm on the same side of the hole as shown in Figure 3. The average fatigue crack growth in 1000 cycles was 1.32 µm/cycle (considering both sides of the hole). The final fracture of the specimen occurred at 9610 cycles.

Figure 2: Plastic deformation just before the fatigue crack initiation (100x magnified)

Figure 3: Microscopic image of the fatigue crack growth (200x magnified)
The microscopic image of the fatigue cracks revealed that the crack growth happened following a zigzag path rather than a straight line. The microstructural grain boundaries of the aluminum material may dictate the path of the crack growth. The mouth of the fatigue crack was analyzed under the microscope with 2000 times magnification factor. The fatigue crack mouth opening at three fatigue cycles (8200, 8700, 9200 cycles) is shown in Figure 4. As the fatigue cycles increased, the mouth of the crack increased. In 1000 cycles starting from 8200 cycles, the crack mouth opened 1.9 \( \mu m \). The zigzag nature of the crack path had also been observed from the exaggerated view as shown in Figure 4.

![8200 cycles][8700 cycles][9200 cycles]

**Figure 4:** Microscopic image of fatigue crack mouth opening (2000x magnified)

### 4. EXPERIMENTAL RESULTS

The fatigue loading was monitored from the MTS control module. As the fatigue cracks begin initiating from the pre-drilled hole and grow up to 10 mm (tip to tip length) for the loading rate of 4 Hz. We noticed that the number of AE hits recorded was significantly increases. For the controlled measurement the loading rate was reduced to 0.25Hz and the AE signals were recorded. The cumulative number of acoustic emissions detected by the piezoelectric sensor increases as the fatigue crack grown longer. This is because of the large number of molecular bonding breaks as the crack grows at higher rate thus releasing the stored energy at a higher rate. The release of stored energy at higher rate preserves the marking as the higher rate of AE signals recorded in the experiments.

![Type I AE signals from the experiment](http://proceedings.spiedigitallibrary.org/)

Several test coupons of the same geometry and same experimental set up were used to generate the repeatability of the AE signals. The test coupons were manufactured from the large single aluminum plate to maintain the same material properties in all the test coupons. The AE waveforms recorded from the experiments are predominantly grouped into three types of waveforms. The waveforms are distinguished based on the similar nature in the time domain as well as in their frequency spectrums. Type I AE waveforms are short length in the time domain as shown in Figure 2. The frequency spectrum of the type I signal shows that they have higher amplitude in the 250-400 kHz frequency band. The “Type II” AE signals have relatively longer time period as shown in Figure 3. They have relatively lower frequency components (30-100 kHz) as depicted in their frequency spectrum. “Type III” AE waveforms that were identified as
mixed type waveforms. They have both components of “Type I” and “Type II” signals and their frequency spectrum also support the mixed nature of the waveforms. However, more than 90% of the AE signals can be classified into “Type I” and “Type II” waveforms. Both types of waveforms appeared in almost equal proportions.

In all three types of signals had the low amplitude noises as shown in the raw experimental time domain signals. These noises are persistently present in the entire length of the time domain. Analyses of the noises showed that they are harmonic in nature and the frequency spectrum of the noises have the frequency spikes at 170, 340, 510, 680, 830 kHz frequencies. These frequency spikes were also present in all three types of signals and they were part of noises. The sources of the noises were the hydraulic unit of MTS machine, electromagnetic control module, servo motor etc. Thus these frequency spikes were not related to AE signals of fatigue crack growth.

5. DISCUSSION OF THE EXPERIMENTAL RESULTS
To understand the underlying physics behind the different types of AE waveforms the physical phenomena can be illustrated in Figure 4 and Figure 5. As the load level reaches to the maximum of the fatigue load cycle, the stresses at the crack tip rises at significant amount that causes the failure of the material at the crack tip. Thus crack grows releasing the stored energy due to extreme stresses at the crack tip and generates AE event. This happens instantaneously while the crack lips are open. This physical situation represents one type of the AE waveforms. The physical phenomena are
illustrated in Figure 4 that is related to the fatigue crack growth. The generated AE waves travel along the crack lips as surface waves.

Figure 8: Physical phenomena for fatigue crack growth

There is another type of physical phenomena that could happen at the lower load level of the fatigue load cycle. As the materials fails at the crack tip during crack growth, it often does not happen uniformly along the entire thickness. In fact the microscopic analysis of the crack surfaces revealed that there exist some irregular waviness natures along the faying surfaces. At lower load level, the crack lips tend to close and especially at the crack tip region, the rubbing, and clapping happens between the faying surfaces as shown in Figure 5. These rubbing and clapping motions of the faying surfaces generate another type of AE waveform. They may generate the plate waves along the cracks.

Figure 9: Physical phenomena for fatigue crack rubbing between the faying surfaces

The third type of AE waveform corresponds to the mixed situation of the two previous phenomena. When the crack happens instantaneously releasing the stored energy, the local stress drop at the crack tip may have some rubbing and/or clapping. These two physical phenomena could happen so instantaneous that the AE waveforms could not be discerned from each other. Thus it may cause the mixed type waveforms as shown in Figure 4. However, this physical phenomenon was not so obvious and reflected in the 10% of the total AE waveforms during experiments.
6. SUMMARY, CONCLUSION, AND FUTURE WORK

In this research, the physics of the acoustic emission waveforms were analyzed based on in-situ AE-fatigue experiments. The AE waveforms could provide the signature of fatigue crack growth. The microscopic analysis of the fatigue crack was performed and showed that the crack advanced following a zigzag path. The crack path might follow the boundary of the weakest grain structures. As the crack grew longer, the mouth of the crack had opened more. The crack initiation happened followed by a plastic deformation as the fatigue loading cycles continued. AE signals triggered as the crack had initiated and started to grow. A dent was observed at the tip of the crack caused by plastic deformation. The AE signals had provided critical signatures before the material broke. The wider specimen had experimented to capture more AE waveforms as the crack could grow much longer than the thinner specimen. A non-reflective boundary around the wider specimen facilitated to capture cleaner AE signals without having any edge reflections. Two distinctive types of AE waveforms were observed that might correspond to two physical phenomena. The crack growth released the AE waveforms at a higher amplitude while the rubbing and clapping motions released the AE waveforms at relatively lower amplitude. FFT of the time domain signals provided the frequency contents of the two types of waveforms and showed two distinctive features in their frequency spectra.

In the future work, a combination of analytical, numerical, and experimental methods would be used to extract the fatigue crack length information from the AE waveforms. Predictive modeling with experimental validation and verification would be used to separate the non-crack related AE event from the crack growth related AE event. Better optical system to visualize the experimental crack growth may be used to strengthen the physics of materials based explanation of the AE waveforms.

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REFERENCES


