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# Classification of Acoustic Emission Signals from Fatigue Crack Propagation in 2024 and 5052 Aluminum Alloys

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**ABSTRACT:** *The characteristics of elastic waves emanating from crack initiation in 2024 and 5052 aluminum alloys subject to static and fatigue loading are investigated through laboratory experiments. The objective of the study is to determine the differences in the properties of the signals generated from static and fatigue tests and also to examine if the sources of the waves could be identified from the temporal and spectral characteristics of the acoustic emission (AE) waveforms. The signals are recorded using non-resonant, flat, broadband transducers attached to the surface of the alloy specimens. The time dependence and power spectra of the signals recorded during the tests were examined and classified according to their special features. Three distinct types of signals were observed. The waveforms and their power spectra were found to be dependent on the material and the type of fracture associated with the signals. Analysis of the waveforms indicated that some signals could be attributed to plastic deformation associated with static tests. The potential application of the approach in health monitoring of aging aircraft structures using a network of surface mounted broadband sensors is discussed.*

**KEY WORDS:** Acoustic Emission, Waveform, Power spectrum, Aluminum Alloy.

## 1. Introduction

An increasing number of civil as well as military aircraft are being required to remain in service well beyond their design life of approximately 20-25 years. All such "aging aircraft" are likely to sustain internal damage due to corrosion and fatigue. Corrosion usually occurs when the aircraft is on the ground and fatigue is associated with pressurization/ depressurization cycles during flight. Fatigue results in the initiation and growth of cracks at stress concentration points and the presence of a corrosive environment exacerbates this process. Corrosion damage to critical parts of an aircraft, if undetected, can be extremely costly with the risk of loss of life as well as hardware in case of catastrophic failure. Continuous inspection and condition based maintenance of aging aircraft components degraded by corrosion and fatigue are key elements in the safe and cost-effective life extension programs of aging aircraft (NMAB-488-2, 1997).

Acoustic emission (AE) is a nondestructive methodology that has been used, with varying degrees of success, to monitor damage evolution in structures subject to service loads. In conventional AE analysis, parameters such as events-count, distribution of signal amplitude, signal rise time, and the RMS energy of the signals have been used to establish empirical relationships between these parameters and damage to the material (Annual Book of ASTM Standards, 1993; Nondestructive Testing Handbook, 1987; Carpenter, 1994). Numerous empirical studies (Lee, 1999; Lim, 2000) have been conducted to examine the correlation between the AE signals and fracture and fatigue damage parameters in a variety of materials (Oh, 1998; Oh, 1999; Takahashi, 1996). It has been shown that under static loading AE analysis can be used to detect the initiation of yielding and that the cumulative AE count from a notched specimen is directly related to the stress intensity factor for cracks emanating from the notch tip (Buttle, 1990). Acoustic emission based methods have also been very useful in detecting crack initiation and propagation in a variety of structures under fatigue loading (Heiple, 1992; McBride, 1981; Friesel, 1989; Scala, 1987; Daniel, 1997).

In order to realize the potential of this general concept to a greater degree, attention has been focused increasingly on the recording and analysis of the individual waves emitted by the sources. For new as well as aging aircraft structures, the most critical damage is the initiation and growth of fatigue cracks from stress concentration points and corrosion sites (cutouts, rivet holes, etc) (Nam, 2001; Nam, 2001). The elastic waves emitted from sudden release of strain energy due to the extension of cracks or other flaws are strongly affected by the detailed nature of the flaws, as well as by the material and geometry of their propagation path (Nam, 1997). Thus, the observation and analysis of the waves generated by microfracture events in a loaded structure can, in principle, lead to the detection of crack-initiation from existing flaws and monitoring their growth during service. In this technique the quantitative relationships between the generated waveforms and the physical mechanisms associated with the source are derived from theoretical models of the various possible failure modes of the structure (Guo, 1996; Nam, 1999; Nam, 2001).

In this paper, the elastic wave signals generated during static and fatigue experiments on laboratory specimens (coupons) of aluminum alloys were recorded in real time, and the waveforms of the individual signals were examined and classified based on their spectral characteristics. The classification can be used to develop algorithms for autonomous health monitoring systems for aging aircraft.

It should be noted that AE-signals in real structures are usually accompanied by noise from a variety of sources. Thus discrimination between signal and noise is of paramount importance in the practical application of AE based methods. An example of a possible practical implementation of the method can be found in (Haugse, 1999), where a distributed system of broadband sensors was used to detect the location and size of a fatigue crack in an F-16 aft bulkhead. The noise generated by other sources was found to be significant in a different frequency range than that for the signals generated by fatigue cracks.

## 2. Experiments

The specimens used in the experiments are 2024-T4 and 5052 aluminum alloys; their geometry and dimensions are shown in Figure 1. The notches were made on one side of the specimens using an electric discharge machine (EDM). In order to reduce noise, the grip sections of the specimens were covered with epoxy, cured by heat treatment for 20 minutes at 80℃.

Fatigue and static tests were performed at room temperature using a servo-hydraulic testing machine (INSTRON Model 8500), under controlled loading cycle. The stress conditions used in the fatigue tests were: $\Delta\sigma$ = 89 MPa, R = 0.67 for the 2024 alloy and $\Delta\sigma$ = 78 MPa, R = 0.5 for the 5052 aluminum alloy. The load cycle was a sine wave of frequency 2 Hz. The static tests were performed under a stroke control of 0.5 mm/min. The slow loading rate was used in order to increase sensitivity and to prevent AE event pile-up. At higher loading rates, several simultaneous events could appear as a single event, and subsequent events could be missed.

The AE measurements were carried out using a Fracture Wave Detector (FWD, Model F4000, Digital Wave Corp., Englewood, Co.). The FWD allows digitization of the waveforms in real time. The digitization rate was set at 12.5 MHz with a 1024 point gate length for each channel using a threshold of 0.2V. Two broadband transducers (DWC B1025), with reasonably flat response to about 1.5MHz, were placed at equal distances of 20mm from the notch (see detail in Figure 1). Two 40dB preamplifiers (AET 140B) with 30kHz-2MHz plug-in filters were used in the experiments.

## 3. Signal Characteristics

A large number of signals were recorded during each test; they were generated by crack extension from the notch tip and also by extraneous noise sources. Typical AE events together with the stress history in a static test is shown in Figure 2. It can be seen that the number of events increased significantly during yielding of the specimen as it approached final failure.

The signals were classified based on visual examination of their temporal and spectral features. The general procedure followed in the visual classification of the signals is sketched in Figure 3. The signals from each specimen were found to be of three general types based on their spectral characteristics. Typical classified signals are shown in Figures 4 and 5 for the static tests, and in Figures 6 and 7 for the fatigue tests. The relative number of observed emissions from fatigue tests on the two alloys are given in Table 1.

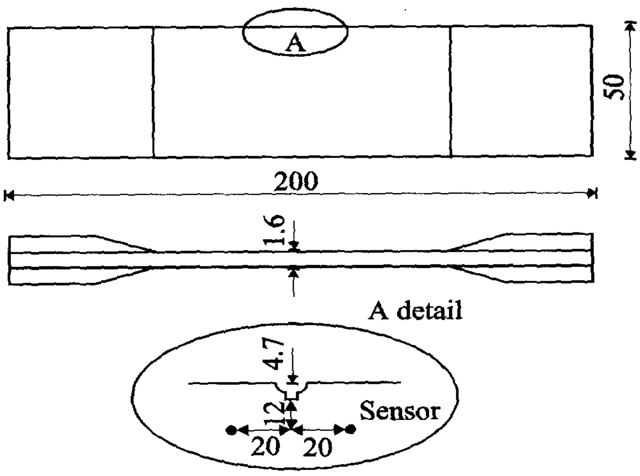



**Fig. 1** Specimen dimensions (unit : mm)

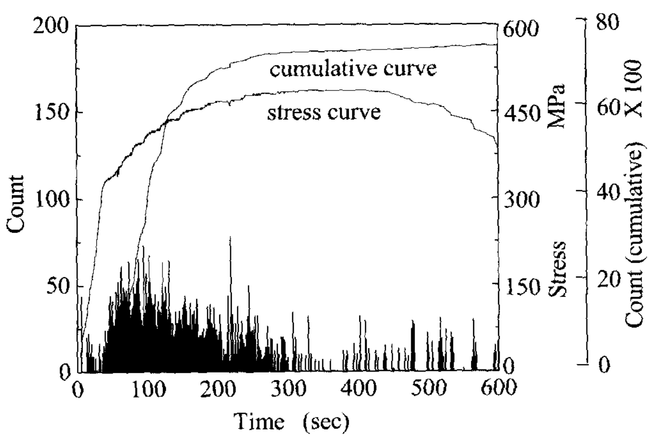



**Fig. 2** AE signals recorded in a typical static test

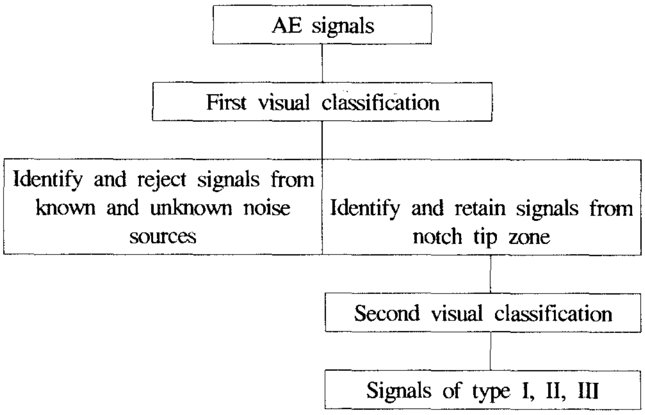
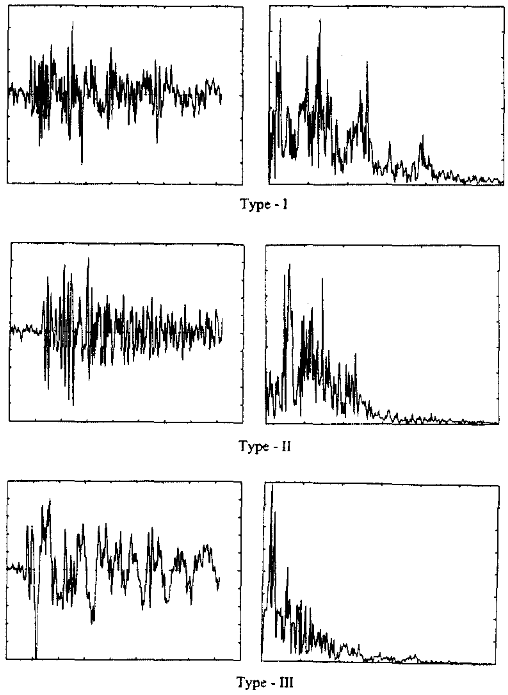



**Fig. 3** Flow chart of the visual classification.

**Table 1** Classification of AE events from fatigue tests

| AE events | Type I | Type II | Type III |
|---|---|---|---|
| % in 2024 Al. | 21.7 | 45.7 | 32.6 |
| % in 5052 Al. | 12.5 | 78.0 | 9.5 |




i) Waveform ii) Power spectrum

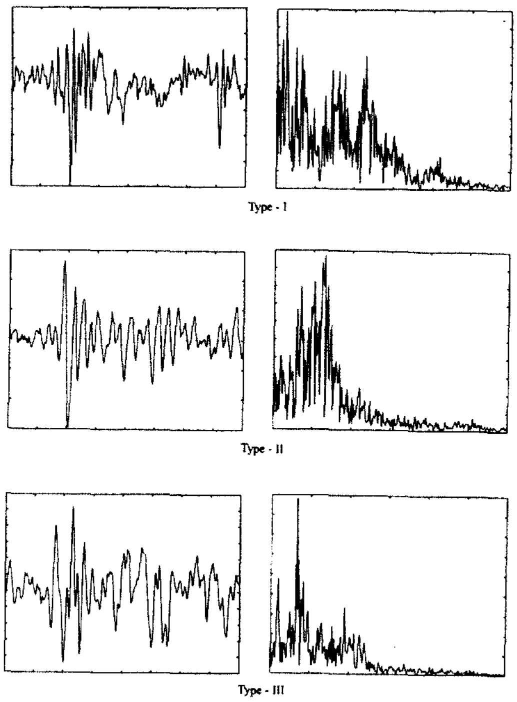
Horizontal scale i) waveform, 5s/div., ii) power spectrum, 0.5 MHz/div. Vertical scale, arbitrary.

Fig. 4 AE events detected during static test in 2024 aluminum alloy

## 4. Source Characterization

It can be seen in Figures 4 and 5 that Type-I signals in both materials have dominant peaks in their power spectra at approximately 0.25, 0.7 and 1.2 MHz. The power spectra of Type-II signals have a dominant peak at approximately 0.4 and 0.6 MHz in the 2024 alloy, and 0.6 MHz in the 5052 alloy. Type-III signals have dominant peaks at approximately 0.15 MHz in 2024 and at 0.4 MHz in 5052. Since crack initiation under static loading is generally preceded by notch tip blunting, appearance of plastic zone, and void formation and coalescence, the spectral peaks are influenced by these phenomena.

The classified signals recorded in a typical fatigue test are shown in Figure 6 and 7. They are again divided into Type-I, Type-II and Type-III signals. Type-I signals have a lower frequency content with dominant peaks at approximately 0.15 MHz and 0.5 MHz in the power spectrum. Type-II signals have characteristics that are similar to plate guided waves (Guo, 1996; Nam, 1999) containing two distinguishable parts as extensional and flexural waves (Wu, 1995). Their power spectra show that the frequency components are spread out over a fairly wide range near 0.5 MHz. The Type-III signal for 2024 Aluminum, shown in Figure 6, is characterized by a very sharply rising and decaying waveform and a strong high frequency component, which implies high energy release. These signals have a dominant peak at approximately 0.6 MHz and another peak beyond 1 MHz. As high frequency components decay rapidly, they have a relatively short duration. The Type-III signal for 5052 Aluminum, shown in




i) Waveform ii) Power spectrum

**Fig. 5** Same as in Figure 4 for 5052 aluminum alloy

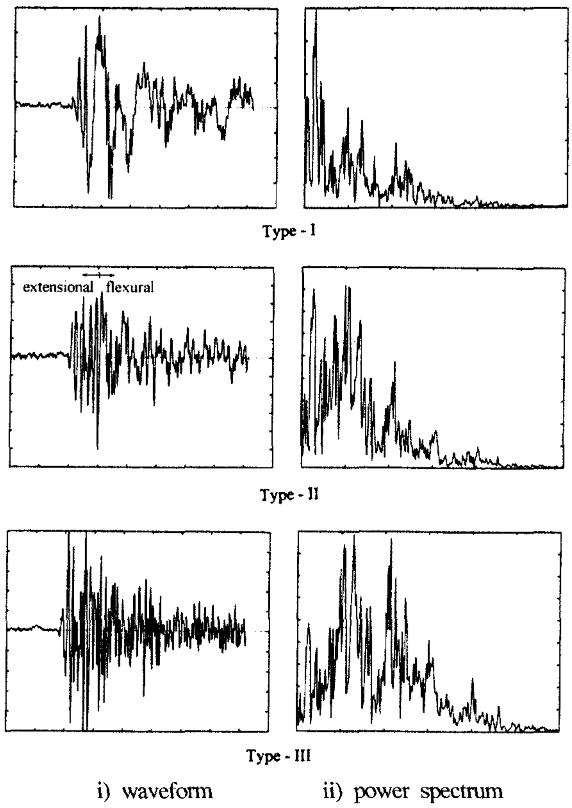



**Fig. 6** AE events detected during fatigue crack propagation in 2024 aluminum alloy.
Scale is the same as in Figure 4.

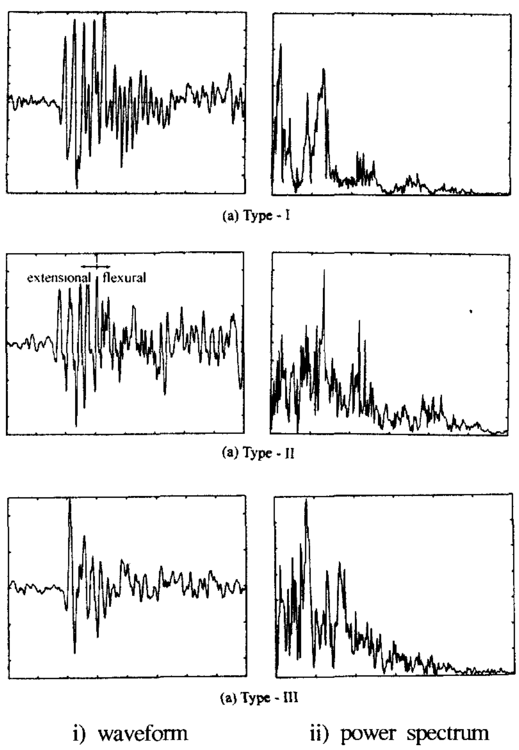



**Fig. 7** Same as in Figure 6 for 5052 aluminum alloy

Figure 7, has dominant peaks at approximately 0.4 and 0.75 MHz. The differences in the properties of the signals can be attributed to the fact that the AE signals are carried by extensional and flexural plate or lamb waves, and that the relative amount of the two types of waves depend on the proximity of the crack to the surface of the plate (Wu, 1995). Thus, as the crack extends through plate thickness, the characteristics of the signals change due to interference between different ratios of the combination of the two types of waves. In addition, different types of AE may be generated from crack initiation and propagation as a function of the loading cycle. The AE signals resulting from crack growth near a peak tensile stress can be caused by the fracture of inclusions in the path of the crack (Bates, 1969). Accordingly, it can be concluded that signals obtained from the fatigue tests are generated by crack propagation. As the stress is reduced to zero, the crack may close, and signals may be generated from crack surface fretting. These types of signals have frequency characteristics that are different from those of the signals from crack growth and can be identified as noise. As the stress increases, the crack surfaces that were mechanically adhered can separate and generate AE according to crack growth.

## 5. Concluding Remarks

The characteristics of the AE waveforms recorded in static and fatigue experiments on two aluminum alloy specimens were investigated using a visual classification method. The signals from crack propagation events were studied in an effort to determine the distinguishing features of the various signal types. The signals in both static and the fatigue tests could be classified into three types (type I, II and III) based on the properties of their waveforms and power spectra. The signals recorded in static tests have been attributed to avalanche motion of dislocations occurring at yielding, and are believed to be generated by the fracture of intermetallic particles and debonding of the particles from the matrix during crack growth. A majority of the events observed during the fatigue tests are believed to be due to rapid crack extension and the transport of the released strain energy as plate guided waves.

The experiments carried out in this study have demonstrated the feasibility of dynamically characterizing the initiation and growth of fatigue cracks in aluminum alloys. Fatigue fracture of high strength aluminum alloys generates numerous acoustic emission events that can be detected by surface mounted broadband sensors. The analysis of the waveforms and their power spectra can be used for real-time monitoring of the evolution of fatigue damage in defects critical structures. However, this will require a better understanding of the wave phenomena associated with crack growth in presence of the detailed microstructural features of the crack tip region through further experiments and theoretical modeling.

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