A COMPARISON OF AE MEASUREMENTS FROM ALUMINUM ALLOYS AND GLASS/EPOXY COMPOSITES WITH DIFFERENT AE TECHNIQUES

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INTRODUCTION

Two separate experiments, using different sample materials and sample geometries have been carried out using a number of different AE techniques and measurement systems. In both experiments the AE generated during tensile loading was measured and characterized. The types of AE measurements used simultaneously on each test included: (1) analog rms voltage measurements of the voltage induced at the piezoelectric transducer attached to the sample, (2) computer controlled standard resonant sensor (140 kHz) parameter measurements such as count, events, rise time, duration, etc., and (3) modal AE measurements providing actual wave forms of the AE events. Modal AE should provide distinct wave modes created by different AE sources. The outputs of both resonant piezoelectric and flat, high fidelity wide band transducers were captured with the waveform system. Each of the two experiments will be discussed separately below.

EXPERIMENT #1

In the first experiment, two different specimen geometries of plain weave glass/epoxy laminates with fiber volume fraction of 62±2% were tested in tension to failure. Each laminate was ten plies of E-glass manufactured by Yokohama Rubber Co., Ltd. and were cut from a sheet that was to be used as the landing gear door of a Boeing 747. One specimen was side notched on both sides of the centerline (called notched samples) and the other was a standard dog bone shaped tensile specimen (called smooth samples.) Specimens

![Figure 1. Rms voltage and applied load as a function of displacement for a notched and a smooth sample.](image)
were 200 mm in length and 20 mm wide. The notch to width ratio was 0.25. All specimens had the same width (hence the same area) at the center. Aluminum tabs were glued on the ends of the samples for gripping. The specimens were pulled in tension at a cross-head speed of 0.01 in./min. in a servo-hydraulic test machine (MTS, 880).

Both types of specimens failed at the specimen centerline. The AE behavior as recorded by an rms voltage meter (HP-3400A) was vastly different for the two geometries as can be seen by viewing Figure 1. The notched samples produced a more “spikey” rms voltage that was somewhat lower in magnitude. The smooth sample produced a rather smoothly increasing rms voltage until near failure. The load curves while similar, have significantly different maximum values due to the stress concentration at the notch. The AE event rate as measured by a parameter based system is also significantly different for the two types of samples, as shown in Figure 2. In the AE event rate (AE events/0.1 sec) for the notched sample, little or no AE is observed until near failure, at which point the AE rate begins to increase rapidly. For the notched specimens the AE rate behavior and the rms voltage behavior are quite similar in nature. Little difference is seen in the AE rate behavior for thresholds of 32 and 40 dB. In fact, they lie nearly on top of each other. The smooth samples produced copious amounts of AE when measured by standard AE parameters. The AE event rate (AE events/0.1 sec) for a smooth specimen, as a function of displacement, along with the applied load is also shown in Figure 2. Data using threshold values of 32 and 40 dB are presented. Notice for a 32 dB threshold a maximum in the AE event rate is observed. This maximum is not real but is an artifact due to the dead time chosen for the AE measurements. In this case, the AE rate has increased to a point that the individual events are coming so fast that the measurement system can no long keep up. Hence, the system can no longer count single events, and the event rate begins to decrease. It is clear that the maximum is an artifact by a comparison of the AE rate behavior with the rms behavior. Also notice for the 40 dB threshold that a maximum does not occur at the same displacement as was observed for the 32 dB threshold. The AE rate for the 40 dB threshold shows an increasing event rate until it reaches the same event rate magnitude as the maximum for

Figure 2. AE event rate and applied load as a function of displacement for a notched and a smooth sample.

Figure 3. Amplitude distribution for a notched and a smooth sample.
the 32 dB threshold which coincidentally happens to be very near final failure. Amplitude distributions for the two different samples are shown in Figure 3. Based on numerous well known reports in the literature, the amplitude distributions suggest at least two different sources.

The significant differences in the AE (both rms voltage and the AE event parameters) for the two sample geometries poses an interesting question. Are there two different sources active in the two samples, or is the measured AE simply strongly dependent on the stress concentration near and at failure? Clearly the notched sample will have a higher stress concentration. The modal AE measurements should be able to answer the question posed above. If different AE sources are operable, they should produce distinct and different waveforms depending on their orientation and position relative to the midplane of the coupon [1]. Figure 4 shows measured wave forms for both a notched sample and a smooth sample. Notice the very strong similarity between the two waveforms indicating the same AE source in both specimens. Similar extensional waves were observed over and over throughout the tests. Precise source location was possible with wave-based algorithms. In both types of samples, it was determined that the AE emanated from a very narrow band on the failure line at the center of the samples. An SEM investigation of the fracture faces from both sample types revealed only a fiber breakage mechanism. In-plane matrix cracking would also produce E-modes like those shown, but no transverse matrix cracking or delamination was expected in this woven material and none was observed.

As indicated above the shapes of the waves from the failure zone looked the same for the notched and smooth specimens shown in Figure 4. Amplitude variations indicating smaller and larger fiber bundles were breaking was also observed. Figure 5 shows data for a double hit (two AE events spaced closely in time) measured by a transducer on the sample center line and by a similar transducer located a distance from the center line. Two interesting facts can be determined from an examination of Figure 5. First, this is clearly two separate AE events. However, they would be measured as one single event by most parameter based systems with commonly used dead times. The signals are too close in time to be discriminated as separate signals. Second, notice that the amplitude tends to increase as the wave propagates through the sample. This may cause a problem in some amplitude distribution data if the amplitudes are measured from sources at different distances from the transducer.

CONCLUSIONS FROM EXPERIMENT #1

Stress concentration leads to AE initiation early on. All three techniques showed this. This has been widely established before. The amplitude distribution shows at least two mechanisms according to the traditional interpretation. Waveforms were the same from AE initiation up to failure for both types of specimens. The lack of variation and identical failure locations indicated only one failure mechanism. This was subsequently confirmed by SEM photos.

EXPERIMENT #2

The AE generated during the plastic deformation of aluminum alloys has been investigated in detail by numerous investigators [2-5]. In particular, the AE generated during the deformation of 7075 aluminum alloys has been the subject of numerous investigations [5-8]. It has been clearly established that the AE generated is strongly dependent on the prior thermal and mechanical treatment of the test materials. The 7075 aluminum alloy is most commonly used in engineering applications in what is known as the T651 condition.
Waveforms from both transducers are shown. Waveforms at yield were captured from both the 7075-T6 and wave theory as presented by Gorman [14]. Figure 6 shows waveforms typical of the AE measured at yield. The discussions will be given in terms of what would be expected from the proposed AE sources. The discussions will be given in terms of what would be expected from plate tempt will be made to relate properties or characteristics of the measured waveforms to what would be expected from the proposed AE sources. An elegant investigation carried out in England [12] has suggested that the AE during fatigue crack growth in 7075 aluminum alloys is due to the actual advancement of the fatigue crack, and work by Heiple et al. [13] has shown that the AE signal produced by deformation in the plastic zone ahead of the growing fatigue crack is too small for the observed AE. The elastic energy released by the actual crack advance is consistent with the size of the AE signals produced. Wave forms of the AE produced during fatigue crack growth have been measured and compared with those measured during plastic deformation at yield. No waveforms characteristic of plastic deformation were found during fatigue crack growth.

Fatigue crack growth in 7075 aluminum alloys was originally believed to be due to the fracture of Mg-Si inclusions by the advancing fatigue crack [9]. This conclusion was based primarily on the remarkable agreement between the number and area-size distribution of the inclusions in a section parallel to the fatigue crack plane and the number and amplitude distribution of the observed AE signals. More recent measurements on 7050 aluminum alloy (an aluminum alloy similar to 7075 with a much lower inclusion content) found fewer AE events, but with amplitudes larger than those observed in the 7075 aluminum alloy [10]. The observations led McBride et al. [11] to propose that the source of AE during fatigue crack growth was intense plastic flow ahead of the growing crack. An elegant investigation carried out in England [12] has suggested that the AE during fatigue crack growth in 7075 aluminum alloys is due to the actual advancement of the fatigue crack, and work by Heiple et al. [13] has shown that the AE signal produced by deformation in the plastic zone ahead of the growing fatigue crack is too small for the observed AE. The elastic energy released by the actual crack advance is consistent with the size of the AE signals produced. Wave forms of the AE produced during fatigue crack growth have been measured and compared with those measured during plastic deformation at yield. No waveforms characteristic of plastic deformation were found during fatigue crack growth.

AE measurements were carried out using a new measurement system called a Fracture Wave Detector (model F40000 manufactured by Digital Wave Corp., Englewood, Colorado. The Fracture Wave Detector allows for the digitization of the total AE waveform. The digitization rate was 12.5 MHz with 1024 bytes per waveform using a threshold of 33 dB. The instrument is capable of capturing 65 waveforms per second on each of four channels. However, this high capture rate was not approached in the present investigation. High fidelity, broadband transducers (Digital Wave Model B1000) were used to detect the AE. The transducers are specifically designed for broadband AE measurements over a frequency range of 50 kHz to 3 MHz. Tensile samples used during the deformation experiments had the following approximate measurements; gage length 5.1 cm, width 1.3 cm and thickness 0.6 cm. All tests were carried out using an MTS-880 deformation machine at crosshead speeds between 0.05 and 0.13 cm/min. Two transducers were used, one at each end of the gage length to insure that the measured AE originated from within the gage volume. However, each transducer was a different distance from the notch in order to see different wave propagation characteristics. Two types of fatigue crack growth experiments were carried out. In one set of experiments, samples similar to the tensile samples were used. For the other set of experiments a larger sample, 30.5 cm gage length, 3.8 cm wide and 0.3 cm thick, was used. In both cases a sharp notch was used to initiate the fatigue crack. Loading was at a constant amplitude in tension-tension fatigue at a frequency of approximately 1 Hz. Two broadband transducers were attached at each end of the gage length. In a number of tests an additional resonant transducer was attached to the test specimen very close to the sharp notch. The crack growth was observed with a high power video microscope capable of 0.001" resolution.

In this section, a number of the captured AE waveforms will be shown and discussed. Space limitations for the proceedings are such that only a few representative waveforms of the different AE sources can be shown. In general, large changes or differences from the waveforms shown were not observed. An attempt will be made to relate properties or characteristics of the measured waveforms to what would be expected from the proposed AE sources. The discussions will be given in terms of what would be expected from the proposed AE sources. The discussions will be given in terms of what would be expected from plate wave theory as presented by Gorman [14]. Figure 6 shows waveforms typical of the AE measured at yield. Waveforms from both transducers are shown. Waveforms at yield were captured from both the 7075-T6 and
the solutionized and quenched samples. The waveforms were similar in nature independent of the sample material. The time duration for all of the waveforms shown is 80 μsec. As can be seen, the waveforms were typically of low amplitude and would often only trigger on one of the transducers. It is known from the earlier works discussed above that the source of the waveforms is the avalanche motion of dislocations. The observed waveforms are consistent with that type of source, basically rapid slip, as shown by the fact that a large flexural mode is present with little or no extensional mode.

Three different types of AE waveforms were observed in the AE peak which occurs at 2-3% strain. The three different types were observed during testing of both the 7075-T6 and the 7075-T651 sample materials. The three different types of waveforms are due to: (1) noise (EMI), (2) fracture of intermetallic particles, and (3) debonding of the intermetallic particles from the matrix. Figure 10 shows waveforms which were due to EMI noise, a nonpropagating source of waveform signals. An examination of Figure 7 shows that even though the transducers were separated several centimeters, both the initiation and time dependent character of both transducers is essentially identical. Figure 8 shows examples of the most common of the waveforms observed during the AE peak at 2 to 3% strain. In general the amplitude was higher than the waveforms measured at yield and the plate propagation characteristics are clearly evident. The AE source producing this type of waveform is due to the fracture of intermetallic particles within the matrix. This conclusion is based on the fact that the nature of the waveforms is consistent with that observed for tensile fatigue crack propagation, which is discussed in detail elsewhere [15]. The third type of waveform observed during the AE peak at 2-3% strain is shown in Figure 9. The waveform is very similar in nature to those measured at yield; compare with Figure 6. The source of this type of waveform is probably due to deformation around or debonding of the particles from the matrix, but this needs further investigation. Analysis of a number of different tests provided the following statistics for the AE peak at 2-3% strain, 66-75% of the waveforms captured could be categorized as waveforms from the cracking of intermetallic particles, 11-18% of the waveforms captured were categorized as debonding of the intermetallic particles from the matrix due to being similar to the waveforms observed at yield, and 10-13% of the captured waveforms were simply noise.
Figure 8. Typical waveforms from the AE measured at 2-3% strain, attributed to the fracture of intermetallic particles.

Figure 9. Typical waveforms from the AE measured at 2-3% strain attributed to the debonding of intermetallic particles.

Figure 10. Typical waveforms from the AE measured during fatigue, small sample. Attributed to extraneous noise.

Figure 11. Typical waveforms from the AE measured during fatigue, small sample. Attributed to crack extension.
The AE during fatigue crack growth was also monitored for the two sizes of samples, as mentioned earlier. In both cases two types of waveforms were observed, one type that could be related to crack growth or extension and the others could be shown to be some type of extraneous noise such as grip noise and EMI. Figure 10 shows waveforms due to extraneous noise captured during the fatigue testing of the smaller samples (5.0 cm gage length). With the two sensor array, it was easy to attribute the waveforms shown in Figure 10 to noise since the waveform shape and propagation time indicated that the source must be outside of the transducer array, i.e. near the grips. Figure 11 shows waveforms due to the crack extension of the fatigue crack verified with the video microscope, the load stamping and the number and repeatability of the crack growth events being consistent with fatigue crack growth. Notice the similarity of these waveforms with those shown in Figure 8, due to cracking of the intermetallic particles. Notice the distinct separation of the extensional and flexural modes due to the larger nature of the sample. The in-plane source motion produces a larger amplitude extensional wave relative to the flexural wave, than does an out-of-plane motion. This is why inclusion fracture and crack advance waveforms look so similar. It was observed that the appearance of a flexural mode coincided precisely with the changes in the specimen from plane strain crack growth as indicated by the fatigue “chevrons”, to plane stress shear crack growth ultimately resulting in specimen failure on the 45° plane of maximum shear. Figure 12 shows waveforms due to crack extension during testing of the larger samples (30 cm gage length). Included in these waveforms is a waveform from a resonant (Dunegan S9204, 150 kHz) transducer for comparison. In this array the resonant transducer is located very near the fatigue crack. During the testing of the larger samples, a significant amount of AE due to grip noise was encountered. Figure 14 shows the waveform captured due to grip noise. A disturbing feature to notice is that when using the resonant transducer, no distinguishable difference exists between waveforms from crack extension and those from grip noise. In all of the fatigue crack measurements, on both types of samples, the majority of the waveforms captured had similar characteristics as those attributed to fracture of intermetallic particles in the tension testing. No waveforms were captured which had the characteristics previously identified with plastic deformation of the matrix or from debonding of the intermetallic particles from the matrix. A surprising result during the fatigue testing is the large amount of AE which could be attributed to noise and, in particular, to grip noise. In some experiments over fifty percent of the measured AE could be attributed to grip noise, even though the experimental conditions would suggest that there was no noise present.

CONCLUSIONS FROM EXPERIMENT #2

The following conclusions were reached as a result of this investigation:

(1) The AE measured at yield during the tensile testing of 7075 aluminum alloys contained only one basic waveform. See Figure 6. The AE has been attributed to avalanche motion of dislocations occurring at the elastic yielding of the matrix.

(2) The AE measured at 2-3% strain during the tensile testing of 7075 aluminum alloys was characterized by three basic waveforms. Approximately 10-13% of the waveforms captured were similar to the one shown in Figure 7. The source of this type of waveform has been attributed to noise or other nonpropagating sources. The identification of the source of the waveforms similar to those shown in Figure 7 was based on the propagation time relationships of the two waveforms. The majority of the AE, 66-75% of the waveforms, was similar to the ones shown in Figure 8. The AE source of these waveforms is believed to be the fracture of intermetallic particles in the matrix due to the striking similarities of these waveforms to waveforms.

Figure 12. Typical waveforms from the AE measured during fatigue, large sample. Attributed to crack extension.
Figure 13. Typical wave forms from the AE measured during fatigue, large sample. Attributed to grip
noise.

known to be from crack advance. The third type of waveform is shown in Figure 9. 11-18% of the total were
of this type which is believed to be due to debonding of the intermetallic particles from the matrix. Notice
the similarity with the waveforms shown in Figure 6.

Two types of waveforms were observed during the fatigue cracking of the 7075-T651 aluminum al-
loys. The majority of the waveforms were believed due to crack extension and are shown for the two differ­
ent size samples in Figures 12 and 13. The waveforms are consistent with waveforms known to be from
crack extension [15], and have similar characteristics with those attributed to cracking of the intermetallic
particles. During fatigue crack growth, no waveforms were captured which could be associated with plastic
deformation. In some cases large amounts of AE which could be shown to be due to grip noise was observed.
See Figure 13. The grip noise was observed even though the experimental conditions would not have sug­
gested its presence. The waveforms from the resonant sensor showed no differentiation of the AE from the
grip noise with that from actual crack extension.

REFERENCES

2. T. F. Drouillard, Acoustic Emission, A Bibliography with Abstracts, 1st ed. (IFI/Plenum, New York,
1979).
5. L. J. Graham, Proceedings of the ARPA/AFML Review of Quantitative NDE, AFML-TR-75-212,