

## APPLICATIONS OF AN ACOUSTIC-EMISSION DATA-ACQUISITION WORKSTATION: II

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### INTRODUCTION

An eight-channel data-acquisition system is used to acquire and analyze acoustic-emission (AE) data from aluminum surface-crack specimens. The data acquisition system and an automatic method of analysis are described in a previous paper [1]. In the current paper, a semiautomatic data analysis method for determining the source locations is described, and the results from tests on aluminum specimens are discussed.

### DATA ACQUISITION SYSTEM

The system shown in Figure 1, described in last year's proceedings, has undergone some modifications. The most significant modification to the system is the use of a common external clock for all the digitizers so that the exact arrival times of the signals of interest can be determined within one sampling period. Previously, the clock signal from one digitizer was daisy-chained to the remaining seven digitizers. This caused the clock of the last digitizer in the chain to differ significantly in phase from the original clock and resulted in uncertainty about the exact arrival times of the signals of interest.

The AE transducers are "pinducers" with a bandwidth of approximately 2 MHz and an active area about 2 mm in diameter. The sources of the signals received by these transducers can be located and resolved to within a few tenths of a millimeter. The pinducers are mounted on the part using the plexiglass fixture shown in Figure 2. With this fixture the minimum spacing between transducers on the same side of the fixture is 12.7 mm, and the minimum spacing between the sides can be adjusted for the experiment. The fixture maintains the locations of the pinducers throughout the calibration procedure and the tensile test, not accounting for strain in the test specimen.

The workstation is capable of acquiring data from one to eight transducers and sampling at a maximum rate of 32 MHz. A brief description of the operation of the workstation configuration used for these experiments acquiring eight channels of data follows. AE signals from eight transducers are acquired, amplified, and sent to eight transient recorders sampling at 32 MHz. Initially, the digitizers are accepting

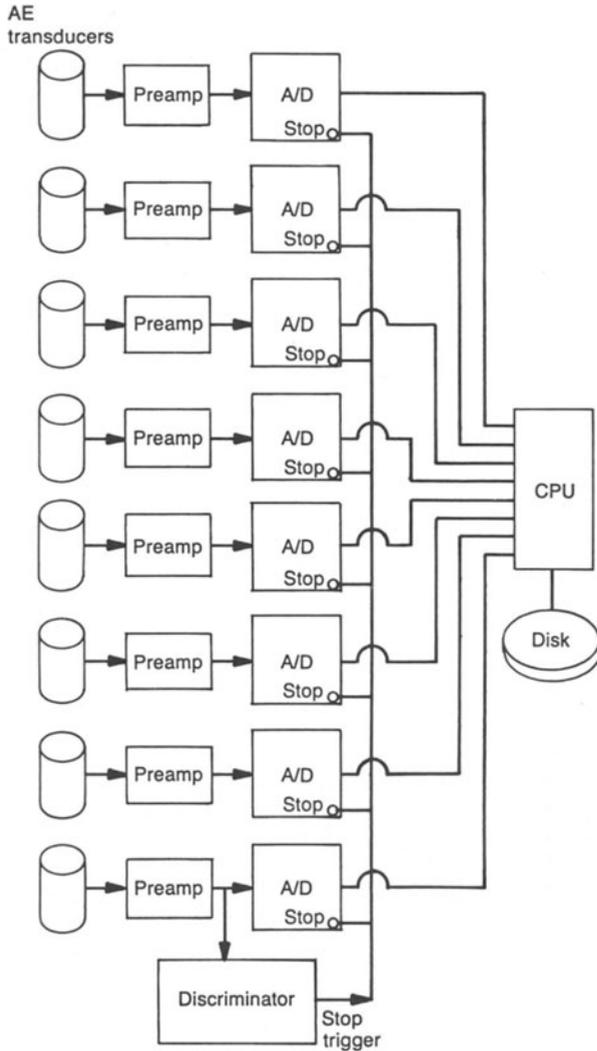


Fig. 1. AE data acquisition workstation block diagram.

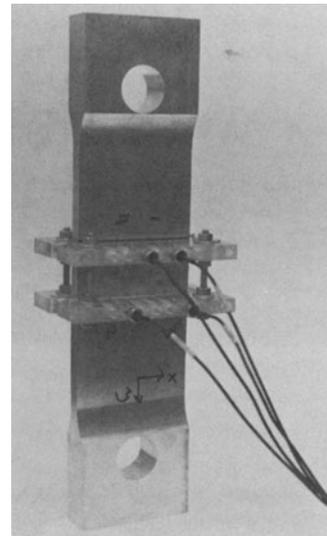


Fig. 2. Aluminum tensile specimen #1 with pinducer mounted in fixture.

data continuously. A stop trigger signal is provided by sending the incoming AE signals from one of the channels to a discriminator which produces an output trigger whenever the input signal on that channel is over a preset level. This stop trigger is sent through an eight-channel buffer which then goes synchronously to each digitizer. Upon receipt of the stop trigger, each digitizer continues to accept data for a preprogrammed period of time. The data are then stored in computer memory, and the system is rearmed and waits for the next stop trigger. The dead time, that is the time the system is unable to accept incoming AE data, depends on the number of channels and the number of data points in each channel. For these experiments, the dead time is approximately 70 ms.

## SOURCE LOCATION CALIBRATION

A calibration procedure similar to that described in last year's work [1] is used to determine the effective location of the transducers on the part. A Nd:YAG laser beam focused to a 0.1-mm spot size generates sound at 32 well defined locations on the surface of the specimen, and the time of arrival of the longitudinal wave for each event is determined for each of the eight channels of acquired data. A nonlinear, least-squares fitting process is used to determine the position of each transducer, based on the known locations of the sources, the longitudinal sound velocity in the material, and arrival times of longitudinal waves from the source excitation. The amplifier gain is intentionally set high to ensure that the longitudinal signal is of adequate amplitude so that the wave arrival time can be determined within one sampling period (31.25 ns). These times are determined by plotting the signal on a graphics computer terminal and having the operator move a cursor to the location of the longitudinal wave arrival. The time is then stored by the computer. After all the times are recorded for the 32 laser source positions, the locations of the eight transducers are calculated. These receiver locations are input values to the algorithm used to calculate the source of acoustic emission events recorded during the experiments.

## SOURCE LOCATION DETERMINATION

In the previous paper, an automatic source location procedure for locating acoustic emission events during experiments is described. The results of a numerical analysis of the procedure showed that the average error in the source location is 0.13 mm in a direction parallel to the crack (the x direction) and 0.27 mm in a direction through the thickness of the part (the z direction). The major source of these errors was the inaccuracy of the automatic system in picking the correct arrival times of the longitudinal wave. Difficulties with the system included an inability to locate the longitudinal wave when the signal amplitude is low and to locate the correct arrival time when the initial rise time of the signal is large.

For these reasons, a semiautomatic method of finding the source locations has been developed. In this method, each signal is drawn on the screen of a graphics computer terminal. The operator picks the approximate start of the longitudinal wave signal and an expanded plot of the signal around the start is drawn. The operator then picks the longitudinal wave arrival time and enters a weight between 1 and 0 indicating the quality of the arrival time selection. The highest weights are assigned to signals in which the arrival time can be determined within at least two sampling periods. A weight of zero indicates that the starting time cannot be accurately chosen, usually due to low signal amplitude and/or noise. Intermediate weights are set for signals with large rise times where the exact signal arrival cannot be determined with more accuracy than three to five sampling periods.

After all eight channels are examined for one event, the analysis proceeds automatically using the selected arrival times and weights. First, a fit is made using all the channels with nonzero weights and the sum of the squares of the residuals is calculated. Then one channel with a nonzero weight less than 1 is eliminated, a fit is made, and the sum of the squares of the residuals is calculated. This is repeated until all channels with a nonzero weight less than 1 have been eliminated one at a time. The process is repeated eliminating these channels two at a time and three at a time. A fit is rejected if the wave arrival time for any channel is more than two sampling periods off that calculated using the

source locations from the fit. The fit is also required to be overdetermined, which means that at least five channels must be included. The source location fitting equations have four unknowns: the three space coordinates and the time of the event. Hence if one channel has a weight of zero, the fits eliminating three of the nonzero weights are not performed.

At the end of this process, the fit with the smallest sum of the squares of the residuals, meeting the acceptance criterion and weighted by the number of channels in the fit, is chosen as the source location for the acoustic emission event. Note that in the process, channels with unambiguous wave arrival times are not eliminated. Channels with less well defined arrival times are included but may be eliminated if they are too far off. The net result of the procedure is a high confidence in the quality of the arrival time identification and in the precision of the final source location.

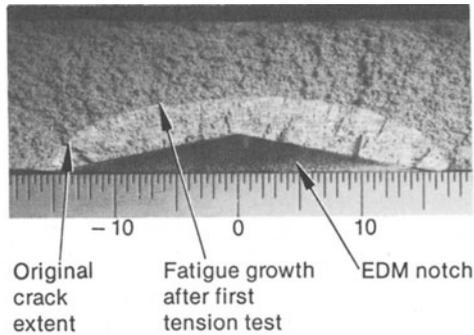
## EXPERIMENTS WITH ALUMINUM SURFACE CRACK SPECIMENS

The goal of this research is to use acoustic emission techniques to identify the locations of crack growth initiation under conditions which simulate those of real structures. Fracture tests with standard specimens, such as compact tension specimens, provide values of fracture toughness for predicting or characterizing fracture in structures. In many cases these predictions are extremely conservative, but they may be nonconservative under the specific conditions of an actual structure. Surface crack specimens are designed to bridge the gap between standard fracture mechanics specimens and actual structures. A notch is first electrical discharge machined in the specimen, and then it is fatigued until the crack grows to the desired size. The AE transducers are mounted on the specimen, and their positions are determined as described above. The specimen is then mounted in a test machine and tested in tension.

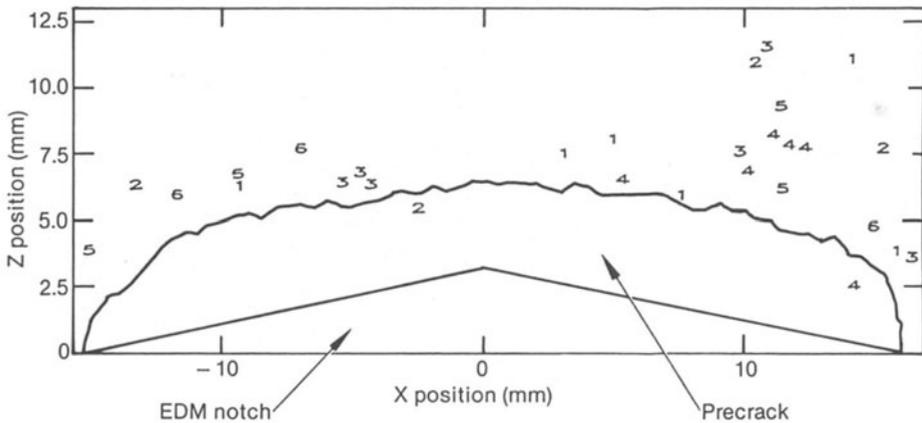
The two specimens in this study, both made of 2124-T6 aluminum, are 102 mm (4 in.) wide and 12.7 mm (1/2 in.) thick with a surface crack in the center. The first specimen had an initial crack length of 31.2 mm and depth of 6.5 mm. The second had a length and depth of 8.3 and 3.8 mm, respectively.

The data acquired during the first loading cycle of the first specimen are described in the previous paper [1]. The extent of crack growth following the first load cycle was marked by fatiguing the specimen prior to the second load cycle, the results of which are presented in this paper. The transducers were remounted and their positions recalibrated. The specimen was then loaded to 377,000 N and this load held for several seconds. The intent was to unload the sample and run a third loading cycle, so the AE system was disarmed and the acquired data from the second loading cycle was written to disk. During the disk write, the crack extended and the sample failed. Therefore, no data were acquired in the final seconds prior to the complete failure of the sample.

The analysis of the data collected during the second load cycle and a photomicrograph from the destructive analysis of the fracture are presented for this specimen in Figure 3. The photomicrograph shows the initial EDM notch and fatigue crack prior to the first loading cycle. The diagram at the bottom shows the location of the initial EDM notch and the initial fatigue crack measured using a cursor on a video image of the specimen. The line of the fatigue growth used to mark the crack extent (~0.5 mm) prior to the second loading cycle is barely visible in the photomicrograph but is well defined on the specimen under the correct



a. photomicrograph of failed specimen



b. AE source locations calculated by fit analysis

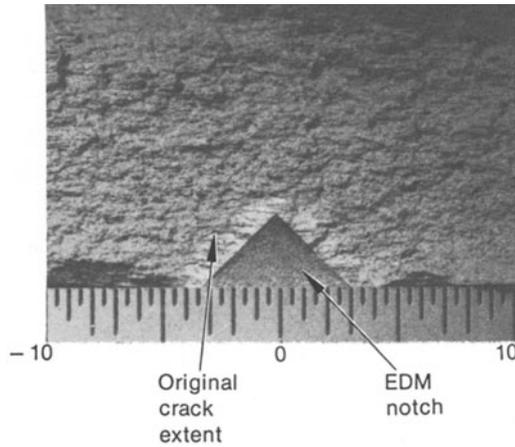
Fig. 3. Tensile specimen #1.

lighting conditions. Locations for 29 of 65 total recorded AE events are also shown. The remaining events have low amplitude in four or more channels or do not converge to a valid location according to the criteria given above. The events are grouped together chronologically, with those events marked by "1" being the earliest events and the last events observed before failure marked by "6".

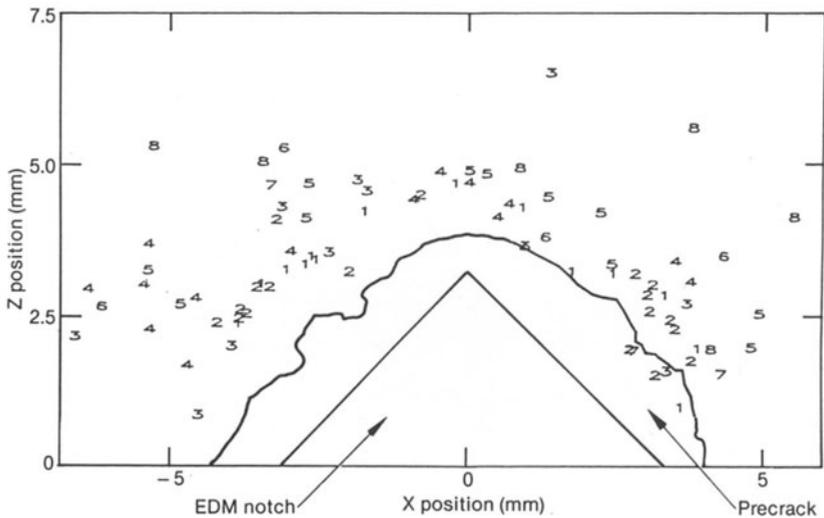
The results for the second specimen with a smaller initial EDM notch and precrack are shown in Figure 4. Specimen 2 was loaded and acoustic emission events were acquired during the entire loading cycle with failure occurring at 514,900 N (115,750 lb). Locations for 86 of 127 recorded events are shown on the plot. Again the numbers ranging from 1 to 8 represent groups of events that occurred at successively later times.

## DISCUSSION

The results for specimen 1 show some events clustered around the perimeter of the original crack and some events clustered in the region between  $x = 10$  to  $12$  mm and  $z = 6$  to  $12$  mm. The photomicrograph shows a large ridge line, a potential failure site, in this second region. In



a. photomicrograph of failed specimen



b. AE source locations calculated by fit analysis

Fig. 4. Tensile specimen #2.

addition, independent evidence indicates that the growth to failure occurred initially in this region. The sample was examined immediately after failure and the photo shown in Figure 5 was taken. The dark areas are regions where the oil couplant used on the transducers had seeped into the crack. The approximate outline of the crack just before failure is clearly seen. Much of the dark area along the top of the photo is due to oil leaking in from the back after the break. This oil stained area connected to the main crack indicates that this region was open before failure since the oil had time to move into this area. Two other areas are apparently connected to the back side of the part in this way, one just left of center and one to the far right. No events are recorded from these regions. For events occurring in the region on the far right, amplitudes of the arriving longitudinal waves would have been small for four of the transducers since they are relatively far away. No such

excuse can be made for missing events in the other region. Another possibility is that these regions grew during the hold immediately prior to failure when no AE data were acquired.

Because of the smaller size of the precrack in specimen 2, the transducers were placed much closer to the crack plane and closer to the center of the crack. The transducers were all 17 to 20 mm from the plane of the crack in the y direction (perpendicular to the plane of the crack in Figure 3) for specimen one. For specimen 2, the transducers are positioned from 8 to 13 mm from the plane of the crack in the y direction. The transducers are positioned in the x direction from 11 to 25 mm from the center of the crack in the first case and from 6 to 7 mm from the center of the crack in the second case. The closer spacing of the transducers on specimen 2 resulted in fewer events being eliminated due to low signal level. The results shown in Figure 4 indicate that most of the growth is confined to a region close to the original crack. A small systematic error in the horizontal (x) direction is indicated by the fact that the locations of the events seem to be shifted about 0.6 mm to the left, relative to the original position of the fatigue crack. This is probably due to an error of 0.6 mm in the absolute position of the laser beam relative to the center of the crack during calibration. The numbers marking the locations indicate the general progression of the crack growth, with the higher numbers corresponding to later events. The six events marked with "8" occurred within 0.89 s of each other at failure. These are, for the most part, farthest out from the original crack.

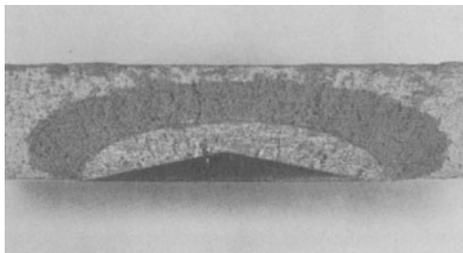


Fig. 5. Tensile specimen #1 immediately after failure with indications of crack propagation direction.

## CONCLUSION

The AE data acquisition system is shown to be capable of providing detailed information about the progress of crack growth in the geometry of the surface crack specimens. The calibration technique using a known laser source allows the locations of the transducers to be accurately determined. From the exact receiver locations and the arrival times of the longitudinal waves, an analysis program is used to accurately determine the location of the acoustic emission event. To increase the versatility of the workstation, future work needs to include tests on ductile steels and ceramics. In addition, the digitized signals acquired from discrete emission events need to be analyzed to determine the nature of the event, i.e., microcracking ahead of the main crack front or macrocrack growth due to ductile tearing.

## ACKNOWLEDGMENTS

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## REFERENCE

1. J. A. Johnson, N. M. Carlson, and R. T. Allemeier, "Applications of a Digital Acoustic-Emission Data-Acquisition Workstation," Proceedings of Review of Progress in Quantitative NDE 8, Plenum Press, New York, 1989, LaJolla, California, August 1988.