DETECTING FATIGUE CRACKS WITH ACOUSTIC EMISSION

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Acoustic emission has emerged as a technique for detecting crack growth in a wide range of materials and has been useful in proof testing structures susceptible to fatigue damage. This proof testing involves removing the structure from service and loading it in an ideal environment. Results of the present study, which is directed towards the use of the acoustic emission technique in an in-service crack monitoring system, indicate that continuously monitored acoustic emission can detect crack growth and failure in a specimen undergoing low-cycle fatigue. Tests with typical aircraft bolted structures show mechanical slippage at the joint. Preliminary results of high-cycle fatigue tests indicate that acoustic emission from crack growth may be detected in a high background noise environment.

Aircraft maintenance, as performed today, requires the periodic replacement of structural parts which are susceptible to fatigue well in advance of their useful lifetimes. This practice is absurdly wasteful and only moderately successful. There is no guarantee that a part not scheduled for replacement will not fail. Compounding the difficulties, it has been established that many aircraft structural materials have poor crack propagation characteristics. For these reasons, a program has been initiated to study the possibility of monitoring the crack growth in high-strength aluminum alloys on a macroscopic level to predict fracture accurately. This monitoring process could take place during periodic ground tests or, more ideally, under normal flight conditions.

One promising method of alleviating these costly and unsafe maintenance practices is through the use of a new technique known as acoustic emission. The term acoustic emission denotes the stress waves generated spontaneously by materials as they deform or fracture. "Tin cry," for instance, is a term used by metalsmiths to refer to the noise created when tin is stressed. Though audible noise has been noted for years, little consideration was given to its usefulness until the 1950's, when Kaiser (1) began his investigations. He detected very-low intensity sound waves in several metals subjected to a slowly increasing load. His most notable observation was that on the second loading of a specimen there was virtually no emission. This phenomenon is now referred to as the Kaiser effect. Most of Kaiser's investigations were done in the frequency range 3-30 KHz, which is particularly susceptible to mechanical and other background noises. Since his discovery, others (2-6) have used increasingly higher frequency bands to alleviate the noise problem. Today it is not uncommon to use frequency bands of 80-120 KHz, 100-300 KHz, or 0.5-1 MHz with great success.

Recent investigations (3) have shown that there are actually two distinct types of acoustic emission occurring simultaneously while a material undergoes stress. The first type is continuous in nature and is associated with microscopic dislocations and slip movements. Twinning, granular reorientations, martensite transformations and, dislocations have all been stated as probable causes. The energy level of these releases has been approximated to be between one and ten electron-volts. The second type has energy levels 10 to 14 orders of magnitude larger than the continuous type and is known as burst emission. Burst emission is due to the fracturing and realignments at the leading edges of flaws and is more random than the continuous emission. This study is concerned with the detection of fatigue cracks by continuously monitoring the burst emission in the stressed material.

ACOUSTIC EMISSION TESTING APPARATUS

A schematic of the acoustic emission system presently being used is shown in Figure 1. The motion caused by the passage of the stress wave is sensed by a resonant piezoelectric transducer. The fundamental resonance of this transducer is 140 KHz. The function of the passive high-pass filter

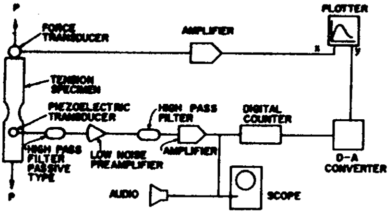

Figure 1. Acoustic emission detecting system.

is to attenuate the lower frequencies before their high levels overdrive the preamplifier and create harmonics in the higher frequency range. This front-end filtering has been of particular benefit in high-background-noise environments. The preamplifier is a high-gain, low-noise type which increases the signal level by 60 to 80 db. The 140-KHz emission signal is mixed with a local oscillator signal and detected to render the emission signal audible. The digital counter is set to count signal excursions above a fixed multiple of the noise level which is approximately 10 μ v at the transducer output. For convenience the counter output is plotted as a function of load, which is measured with a conventional force transducer.

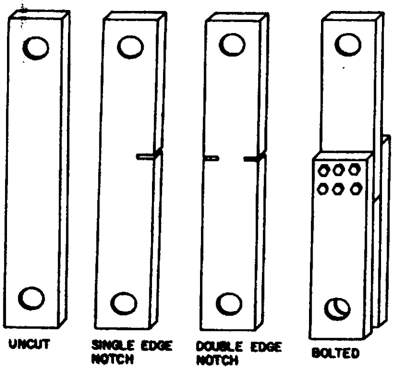

Figure 2. Specimen configuration.

The specimen configurations which have been used are shown in Figure 2. Quarter-inch-thick aircraft quality 2024-T4 and 7075-T6 aluminum plates have been used exclusively. Three of the specimens are single plate type either uncut, cut from one edge, or cut from both edges. The fourth type is double lap-jointed and fastened with six ¼-inch aircraft bolts.

Two types of loading devices have been used for the tests. The first is a conventional hydraulic tensile testing machine with relatively quiet operation. The second is a deflection-controlled plate-flexure fatigue machine with maximum deflection of 2 inches and speed range from 750 to 2000 cycles per minutes. Mechanical action and relatively high speed contribute to the noisy operation of this machine.

The fixtures for transferring the force to the specimen on the tensile load device were designed and built especially for these tests. This was necessary because the conventional specimen grips cause local plastic deformation and slipping which result in unwanted acoustic emission activity. Figure 3 shows the configuration of the new fixtures and how the load is transferred. The fixture and pin were constructed of mild steel and designed to operate well within their stress limitations.

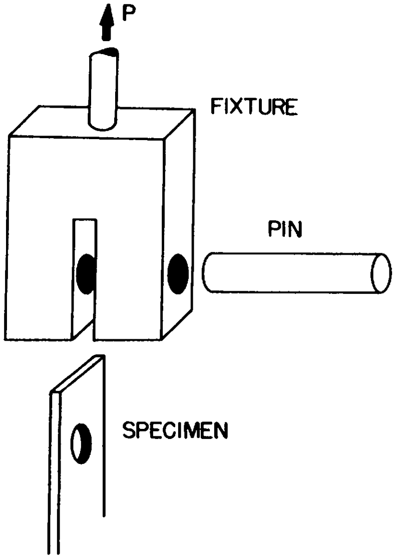

Figure 3. Specimen holder.

ACOUSTIC EMISSION TESTS

Several rising-load tensile tests were conducted on uncut specimens to check the operation of the instrumentation and loading system. The reproduction of results, as shown in Figure 4 and reported elsewhere (6), verified the suitability of the system for detecting acoustic emission.

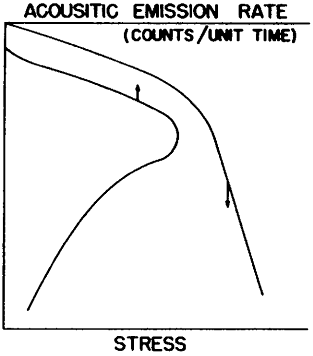

Figure 4. Typical acoustic emission rate vs. strain for an unflawed tensile specimen.

Low-cycle fatigue tests

Figure 5 shows typical results of the acoustic emission from a single saw-cut specimen of 2024-T4 aluminum subjected to cyclic loading ranging from 1 to 14 kips. The high emission count on the first cycle and the subsequent lower counts on the next few cycles is exemplary of the Kaiser effect mentioned earlier. Note also the high emission activity just prior to failure. Figure 6, which is a plot of the cumulative acoustic emission count versus load, shows the same basic trends from a similar specimen. Once again note that a high emission count occurred on the first loading, followed by many cycles with relatively low emission counts and then high emission activity in the cycles just prior to failure. The growing emission count at the end of these fatigue histories is the key to the use of this technique for failure prediction.

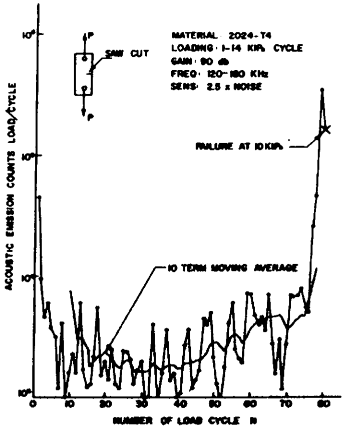

Figure 5. Acoustic emission versus cycles for 2024-T4 aluminum.

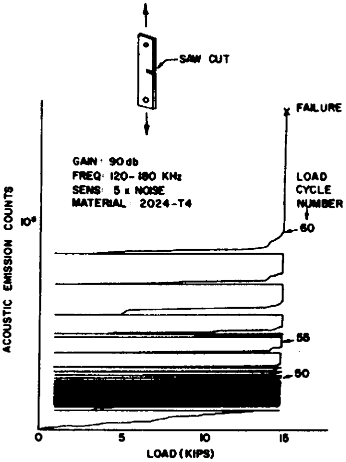

Figure 6. Acoustic emission from a fatigue crack.

Figure 7 shows typical results of a series of tests performed on bolted specimens of 2024-T4 aluminum. The configuration of these specimens is shown at the top of the figure. The four plots shown are cumulative acoustic emission count as a function of applied load. The specimens were loaded from 0 to 15 kips for 15 cycles. In Figure 7 (a) the specimens had well-fitted bolt holes and 60 in-lb of torque on each bolt. The plot is almost identical to that obtained (but not shown) from a single plate uncut specimen under the same loading. The bolts

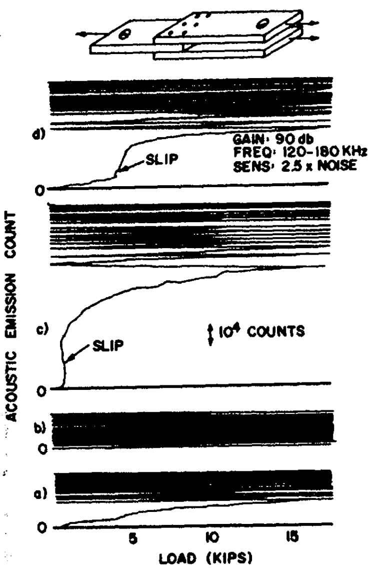

Figure 7. Background noise in bolted specimen.

were then loosened, retorqued to 20 in-lb, and loaded for 15 cycles. The emission history, Figure 7 (b), is almost identical to that of (a) except for the reduced first-cycle count due to the Kaiser effect. The plots shown in Figure 7 (c) and (d) are for specimens with over-sized holes in the center plates to simulate worn joints. The bolt torques were 30 and 120 in-lb, respectively. Note the characteristically sharp increase in emission count at low load in the first cycle indicating slip.

Conclusions drawn from the jointed specimen tests are that the noise produced by a simple well-fitted joint is less than that generated from a growing crack and that the noise created by slip in a poor joint can easily be distinguished from crack emission.

Grip noise

Despite the fact that the grip design has been recommended for acoustic emission testing (7), an unexpected, intermittent, and audible noise was generated from the area of the fixture. In almost every case the noise would occur after about 50 quiet cycles, on the unloading phase and at a particular load value. It is evident from Figure 8 that the magnitude of the unwanted noise grows to a level comparable to that of the highest emission from the propagating crack just prior to failure.

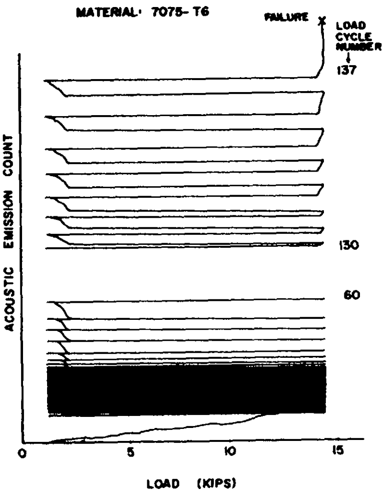

Figure 8. Noise generated from fixture.

Upon examination of the fixture pins, galling at the specimen-pin interface and the surface of the hole in the specimen was discovered. No further irregularities were evident. Though an explanation of the recurring noise has not yet been formalized, the galling of the specimen-pin interface is suspected of being the source.

One possible explanation of the galling is that the hole in the specimen may be stretching around the pin as the load is increased. At some particular low load value in the unloading phase, the static friction may be overcome allowing rapid relative motion of the hole surface around the pin. After several cycles of this rubbing, the surface may be rough enough to cause the resulting noise to be picked up by the transducer. Due to the softer nature of the 2024-T4 the specimens may have been yielding slightly around the pins and not rubbing. No galling has occurred while testing specimens made of 2024-T4.

A temporary solution to the galling problem has been to replace the soft steel pins with high strength steel bolts. As an added precaution the bolts have been meticulously polished and lubricated. The noise problem has been greatly decreased by using the bolts but is not completely eliminated.

Comparison of aluminum alloys

For a comparison of the emission properties of the two aluminum alloys, the specimens were machined to the same configuration and loaded cyclically to the same value. The emission-sensing equipment had identical settings and the tests were performed consecutively.

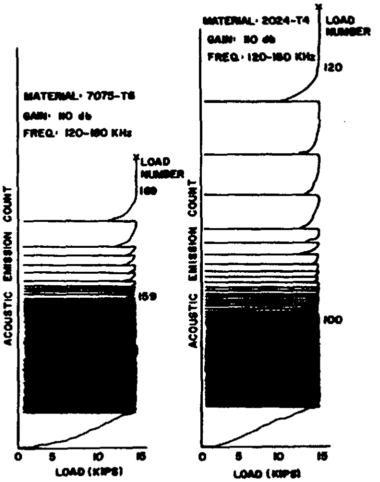

FIGURE 9. Comparison of emission histories of two aluminum alloys.

Figure 9 is a comparison of the 2024-T4 and 7075-T6 alloys with the single saw-cut configuration. The loading was cycled from 1 to 14 kips and the gain was set at 110 db. The emission patterns are similar except for two noticeable details. In the 7075-T6 the noticeable emission indicating part failure occurs later in the life of the part and the part life is extended to a greater number of cycles.

The longer fatigue life of the 7075-T6 could certainly be expected from a comparison of their material properties. The 7075-T6 has a yield strength of 73,000 psi while yield strength of the 2024-T4 is only 47,000 psi. The 7075-T6 alloy is simply being loaded to a smaller percentage of its yield load. An explanation of the differences in the failure emission can also be given from a material properties viewpoint although it requires a greater understanding of the fracture mechanics involved.

Due to the configuration of the specimen, a well defined stress concentration is apparent at the base of the notch. As the specimen is loaded, the region of the notch base is subjected to a stress slightly above the elastic limit of the material. The localized plastic deformation at this point gives rise to the rapid initiation of subcritical cracks. At some value of fatigue loading, the crack growth rate is great enough to produce an emission recognizable with the use of acoustic emission-sensing equipment. On subsequent loadings the crack growth rate increases and, to some degree, the emission does as well. Eventually the crack becomes critical and the part fails. The length of the critical crack is, therefore, an important parameter of the fracture mechanism. It is well known that the critical crack length of 7075-T6 is less that of 2024-T4 for identical geometry and loading. As a result the crack present at the time of failure in the 7075-T6 specimens is shorter than the one in the 2024-T4 specimens.

It has already been mentioned that the crack growth rate governs the emission on a particular loading. Since the 7075-T6 specimens cannot produce a crack of substantial size before critical length is reached, only a few cycles of high emission could be expected. The crack growth rate in the 2024-T4 specimen, on the other hand, continues through the formation of a relatively long critical crack. Thus prior to failure of the 2024-T4 specimens, a greater number of loadings will exhibit high emisison.

High-cycle fatigue tests

Several high-cycle fatigue tests have been conducted on specimens made of 7075-T6. The plate flexure device used for these tests provided displacement-controlled cantilever loading. The specimens had dimensions of 1/4 x 2 x 9 inches with a 1/8-inch-wide notch machined into each side. The fatigue machine was set to cycle the specimens at a rate of 20 Hz and deflect the free end down from the neutral position as much as ¾ inch.

The mechanical noise from this machine was considerably higher than that of the hydraulic testing machine used in the low-cycle tests. It was, therefore, necessary to include the passive filter mentioned earlier. With filtering, the test results closely correlated expected trends noted in the low cycle fatigue tests.

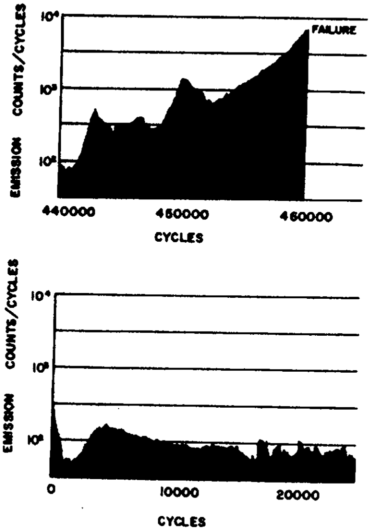

FIGURE 10. Acoustic emission from high-cycle fatigue test.

Figure 10 shows the first 20,000 cycles and the last 20,000 cycles of a typical high-cycle test. The dip and quick rise in emission early in the loading history is characteristic of all the high-cycle fatigue tests run thus far. Though this phenomena has not been thoroughly investigated it is probably due to the formation of subcritical cracks and impurity migration throughout the specimen. The part of the history not shown is a gradual decrease to a level of very low emission which lasts through most of the life of the part. Much of this sustained noise level is due to the looseness in the crank bearings of the loading device and an occasional burst emission from the specimen. Near failure, the emission increases to a very high level and the crack appears on the surface. The crack growth rate and emission level increase until the specimen is fractured.

CONCLUSION

It is concluded from these observations that a growing fatigue crack can be detected using acoustic emission in the presence of a moderate amount of noise due to slip in mechanical joints or noise of rotating components. The acoustic emission from the growing crack may be used as an indicator of impending failure but only in a comparative way. That is, an emission history for cracks growing to failure in the particular part configuration must be available.

The successful application of acoustic emission to monitor the structural integrity of a complex structure, such as an aircraft, will depend on the charactertistics of the background noise and the effects of a random load history on the acoustic emission from propagating cracks. Considering the benefits that may be realizable, we believe that continued research in this area is justified.

ACKNOWLEDGMENT

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