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ACOUSTIC EMISSION TECHNIQUES IN MATERIALS RESEARCH

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July 9, 1970

This paper was prepared for submittal to
Proceedings of the Symposium on Advanced Experimental
Techniques in the Mechanics of Materials and for
presentation at the Symposium in San Antonio, Texas,
September 9-11, 1970.

CONTENTS

ACOUSTIC EMISSION TECHNIQUES IN MATERIALS RESEARCH*

by

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ABSTRACT

A review of the application of emission analysis to evaluate materials properties and defect structure is presented. Topics discussed include fracture toughness and crack propagation, fatigue, plastic deformation, and creep processes in metals, composites, and rock materials. The status of emission techniques as applied to the evaluation of structural integrity is reported. A complete discussion of experimental techniques and data acquisition and processing systems is given. We conclude that acoustic emission techniques have wide applicability to experimental studies in materials research and to evaluation analysis of structural integrity. Directions of future developments and applications are discussed.

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*Work performed under the auspices of the U.S. Atomic Energy Commission.

NOTATION

a	flaw size
A	sheared area
ΔA	incremental area swept out by a crack
B	constant
C, C'	proportionality constants
D	constant
E	modulus of elasticity
E_f	elastic modulus of a fiber
G	shear modulus
Σg	summation of amplitudes of acoustic emission pulses
K	stress intensity factor
ℓ	grain diameter
m	one-half mass of grain
M	constant
n	number of fatigue cycles to the working stress
$\dot{N}$	acoustic emission count rate
N_t	total number of acoustic emission counts observed during a proof test
ΣN	summation of acoustic emission counts
s	distance grain slipped
t	time
V_s	sound velocity
ϵ	uniaxial tensile strain
ϵ_f	tensile strain in fiber
σ	applied tensile stress
σ_f	tensile stress in fiber

σ_p	proof stress
σ_s	driving stress
σ_w	working stress
ω	energy change accompanying slip
$\omega(\epsilon)$	percentage of broken fibers as a function of strain

1. INTRODUCTION

1.1 General

Acoustic emission may be defined as the pressure or stress waves generated during dynamic processes in materials. In the laboratory, acoustic emission techniques have been used on materials as disparate as single-crystal aluminum and wooden beams; applications have been found as diverse as studying earthquake models, testing large missile casings, and evaluating bridge integrity. Most of the published work has been directed to plastic deformation and initiation and propagation of cracks. Also, considerable work has been accomplished in rock mechanics.

Regardless of the phenomenon studied, material used, or the application, one point becomes obvious; acoustic emission analysis is very sensitive to local transient instabilities. A materials system will proceed towards its lowest energy state, and (in most situations) will develop unstable conditions locally well before the whole mass becomes unstable. These conditions result in local dynamic movements, such as formation of a slip-band or platelet of martensite, propagation of a crack or Luders line, sudden reorientation of a grain boundary, bubble formation during boiling, or earth fault movement during an earthquake. In many materials systems, local instabilities frequently cause catastrophic failures. For example, the stresses in a metallic structure may be generally well within the elastic design limit; however, the region near a flaw or crack may undergo plastic deformation from localized high stresses (stress intensity). In this situation the flaw is a generator or source of acoustic emission activity.

This communication discusses the basic principles of the experimental design and techniques of acoustic emission analysis. The historical background is presented, use of the techniques for materials research is reviewed and evaluated for various types of materials, and application of emission analysis in evaluating the structural integrity is reported. Comments about future developments are contained in a final section.

1.2 Background

Historically, the earliest use of "acoustic" emission analysis occurred in the study of seismology. Analysis of the elastic waves produced by an earthquake was used to characterize fault movement in terms of energy released, location, and depth. The possibility of detecting rockbursts in coal mines was appreciated at an early date. In 1923, Hodgson(1) proposed use of subaudible noises to predict rockbursts and earthquakes.

Early observations of acoustic emissions in metals were made by tinsmiths who noted "Tin cry" or twinning during deformation of tin. (Twinning deformations in general are active generators of acoustic emissions) Audible sounds or "clicks" noted during heat treatment of steels were later related to the martensitic transformation. Later studies(2) showed that martensitic transformations in general are copious emitters of acoustic emissions. Crussard et al.(3) reported sounds from metals just prior to their failure. Mason et al.(4) suggested that dislocations in a fine structure produce high frequency vibrations. Other investigators have also reported acoustic vibrations.(5-7)

The first clearly documented serious investigation of acoustic emission was made by Kaiser(8) in 1950. He reported that all metals examined (zinc, steel, aluminum, copper, and lead) exhibited the emission phenomenon. Working with polycrystalline specimens, Kaiser concluded that acoustic vibrations originate in grain boundary interfaces. Emissions were believed to be associated with the interaction induced between interfaces by applied stress. He noted that, for a given material, characteristic spectra of frequency and amplitude existed and were related to the stress level.

In 1955, Schofield(9-11) initiated an extensive investigation of acoustic emission phenomena. He found that the emissions did not originate entirely from grain boundaries, as single crystals also emitted. Also, characteristic spectra of frequency and amplitude were not found, from which Schofield concluded that frequency and amplitude were not the correct fundamental quantities to characterize the emission process.

Tatro(12) became interested in acoustic emission in 1956 and explored the possibility of detecting slip in metals with sonic techniques. From studies on single-crystal aluminum, Tatro and Liptai(13) reported that emission activity was related to pileup and breakaway of dislocations. Anodic surface layers applied to the aluminum crystals changed the emission spectra and acted as effective barriers to dislocation and slip band formation at the surface.

Most early studies of acoustic emissions were associated with plastic deformation or crack propagation in metals. The frequency range used in most investigations was below 60 kHz. A significant advance in experimental technique was the extension of experiments into the 100 kHz and 1 MHz ranges, first reported by Dunegan, Tatro, and Harris.(14) This eliminated the need for elaborate sound-proof facilities by eliminating the effects of extraneous laboratory noise, thereby enabling extension of emission analysis to practical applications.

Since the middle 1960's, applications of acoustic emission techniques to materials research, material evaluation, nondestructive testing, and structural evaluation have increased rapidly. In addition, emission techniques have been found for such uses as boiling and cavitation detection in fluid systems.

2. EXPERIMENTAL DESIGN

2.1 Essential Principles

The principal constraints on acoustic emission systems design are imposed by the magnitude and time duration of the signal from the acoustic emission source.

So that the nature of this source can be better understood for the system design arguments that follow, a model event will be described in some detail. The event is hypothetical but conceptually possible, and it gives rise to energies, time durations, and frequencies consistent with most (perhaps all) of the acoustic emission records taken to the present.

Consider one grain of a polycrystalline material, surrounded by its grain boundary. Assume that the grain is roughly spherical with a diameter $\ell = 5 \times 10^{-3}$ in. During straining, the upper half of the grain slips over the lower half by a distance $s = 1 \times 10^{-3}$ in. A shear modulus $G = 4 \times 10^{6}$ psi is assumed. The stress driving the deformation is taken to be $\sigma_s = \frac{sG}{\ell}$.(15) The energy change accompanying the slip is then estimated as

$$\omega = \frac{GAs^2}{2\ell} \cong 10^{-12} \text{ in.-lb} \qquad (1)$$

where A is the sheared area.

Assume that the slip event is sudden, progressing at half the shear wave velocity of sound in the material.(16) An estimation of the time duration of the primary event is

$$t = \frac{\ell}{V_s/2} \cong 2 \times 10^{-8} \text{ sec} \qquad (2)$$

Now consider the initial event as an impulse which sets the grain in resonant vibration, with the upper half shearing over the lower half. An estimation of the frequency of such a vibration is

$$\omega = \sqrt{\frac{2AG}{\ell m}} \cong 1.25 \times 10^{7} \text{ rad/sec} \cong 2\text{MHz} \qquad (3)$$

where m is half the mass of the grain (assumed to be aluminum).

Other estimations lead to somewhat higher frequencies. If the grain is considered a bubble, a frequency f ~ 50 MHz results. If one considers a pulse reverberating in the grain, with reflection and mode conversion at each boundary, the frequency of the longitudinal component is f ~ 25 MHz.

Such estimations vary with the size and density of the model grain, with the dislocation-connected event assumed, and with the material.

This estimation, however, serves to establish a frequency in the range of 1 - 50 MHz as plausible for acoustic emission events.

It can be assumed that the grain boundary will have a damping influence on the self-excited vibration described above. A reasonable form from the primary acoustic emission event is

$$f(t) = F_0 e^{-kt} \sin \omega_1 t \tag{4}$$

where F_0 is initial amplitude, k is a damping factor, and ω_1 is a frequency as estimated above. It is likely that such an event will give rise to a pulse train of a somewhat lower frequency at the surface of a specimen.(17) The arguments which follow do not depend on Eq. (4) being correct in form. Any fast pulse with similar time duration will suffice.

Armstrong has presented arguments(17) which can be translated to consideration of acoustic emission from stably growing cracks in a test specimen. The frequency range containing the preponderance of energy will be roughly the same, perhaps somewhat lower. However, the energy content of the pulse could be greater by an order of magnitude or more.

The transient pulse train described in Eq. (4) is capable of exciting either a specimen resonance or a resonance in a transducer crystal attached to the specimen. Most investigators have used one of these resonances to detect an acoustic emission event.

The transducer type most used to detect acoustic emission events has been the piezo-electric crystal. Several piezo-electric crystal elements have been used by the investigators, but the most popular crystal element at present is lead zirconate titanate (PZT-5). While the g-constants of 45° Y-cut Rochelle salt appear more favorable, there are several disadvantages to its use, one of which is unavailability. Since the signals to be detected have very low amplitudes, both noise output and sensitivity of a crystal transducer must be considered. The PZT-5 element is preferred because of its low impedance.

Other types of transducers have been used to detect acoustic emission signals.(18) Results indicate that use of other than piezo-electric transducers is justified only for special studies. One should expect a great many additional instrumentation problems to result.

Because of the low signal levels encountered in acoustic emission studies, the transducer must be in contact with the part. Coupling agents used with contact transducers in conventional flaw-detection work are satisfactory. However, a method has been devised and described(19) for testing acoustic emission on parts too small for contact transducers.

As the sonic signal received by a piezo-electric transducer from an acoustic emission event is quite small, the electrical signal generated by it is also quite small, and electronic amplification is required. The basic requirements for such an amplifier are an input noise level, with the crystal attached, on the order of 10 microvolts and a gain of about 1000. Cascaded amplifiers can be used for the necessary signal gain.

Acoustic emissions accompany changes of stress and temperature in a specimen. Usually they have been studied as the specimen is stressed, as acoustic emission is very great near the yield point. Since it occurs in very localized volumes, acoustic emission can be detected below the gross yield in specimens containing flaws (discussed later in this paper). Design of mechanical load trains must be given serious consideration if meaningful acoustic emission tests are to be performed.

Sonic signals similar to acoustic emission signals can be generated at rubbing surfaces, screw threads, gear trains, hydraulic valves, pinned joints, etc. Thus, acoustic isolation of the acoustic emission specimen from the loading mechanism is essential. As many such signals have frequencies lower than those from acoustic emissions, both mechanical and electronic filtering are useful aids. Selection of a piezo-transducer operating in a frequency band well above that of most such extraneous noises is very helpful. Mechanical load trains must always be carefully studied and checked to make sure they are not generating acoustic emission artifacts.(26)

2.2 Instrumentation Systems

The basic information recorded in a typical acoustic emission test is the rate at which acoustic emission events occur as a function of changes of the load parameter or, alternatively, the total of events that have occurred up to the current point in the test. One typically does not acquire meaningful information about amplitude and time distribution of energy in a single acoustic emission pulse, for reasons that will be explained below.

Details of the acoustic emission event are not normally wanted. However, an indication of when an event has occurred is, and electronic counting techniques may be used to acquire data.

One works very close to the system noise level in the typical test. Indeed, some acoustic emission events produce pulses smaller than the largest electronic noise pulses. Proper biasing of the counting equipment is therefore essential and must satisfy two primary requirements. The first is that the trigger of the counter can be set to a predetermined signal amplitude reliably and with small jitter. The level selection feature must be reliable both for transient pulses and for steady state sinusoids. The second requirement is that the counter must contain a time interval gate, so that a rate of occurrence for acoustic emission events can be inferred. Many of the available counters have these two features. However, some do not, and it is generally more economical to choose a counter with them built in than to arrange for them externally.

Amplifiers with logarithmic outputs, with a satisfactory range of sampling times, and with frequency response in the range of most of the acoustic emission signals (as seen at a point beyond the piezoelectric crystal) are becoming available on the market. These instruments are an alternative to the use of an electronic counter. Since the range of rates of occurrence of acoustic emissions in a single test can be five orders of magnitude, these systems have considerable appeal.

Two acceptable ways of processing acoustic emission data on-line have been described above. On-line computers have also been utilized for extensive processing of acoustic emission data. Data have also been recorded on parallel channels with suitable high-speed tape recorders for off-line processing by a large computer or reprocessing the data in a different way. Many times, however, comparatively simple on-line processing extracts the most important information.

A simple and economical method of processing data from the counter system is feeding it to a digital-to-analog converter having an output voltage proportional to count rate or total count, according to the choice of the investigator. This output can then be displayed on one axis of an

X-Y recorder, while the other axis displays a conventional engineering parameter such as load or pressure. A histogram-like display results. This method of display has proven very useful in developing acoustic emission characterizations of materials for quality assurance tests. Figure 1 is an example of such a record. The same procedure is useful in basic studies of materials.(20) When a logarithmic amplifier is used in place of the electronic counter, the output data can be displayed directly on an X-Y recorder, provided a suitable choice of sampling time is made.

Elaborate methods of processing and displaying data from a number of acoustic emission channels simultaneously have been devised in recent years to aid in locating the position of acoustic emission origin on large parts. Briefly, a method of triangulation is devised, sometimes with several degrees of redundancy, based on first arrival times of acoustic emission signals at various transducers in an array. The arrival time data plus knowledge of the speed of sound in the test part permit determination of the zone generating the signals. More will be said about such tests later.

The location of the emission source can be located to within about two inches at best. Post-processing of the record tapes by a computer is necessary. The limit of distance discrimination is dictated by two facets of the test: Finite rise time of the first arrival pulse; and skew error of the magnetic tape as it crosses the recorder-playback heads.

2.3 Frequency Response and Detection Fidelity

Prospects are dim for devising a measuring system to detect and record (with good fidelity) a true acoustic emission signal as it is produced at the source. Some reasons for this and some of the design problems that must be solved before it can be done are discussed in the following paragraphs.

The model source discussed above led to the conclusion that Eq. (4) was a reasonable form to expect for the source signal. In addition, twinning, martensitic phase transformations,(21) intermittent progression of stable cracks, breakaway of dislocations from pinning sites, collisions of rapidly moving dislocations with obstacles, and interaction of dislocations with surfaces are known or thought to be acoustic emission sources. They should all originate as impulse phenomena and have time durations in the 0.01 to 1 microsecond band already described.

Figure 2 contains plots of the Fourier integral transform phase and amplitude of a signal described by Eq. (4), where ω_1 is 6.28×10^6 rad/sec and k corresponds to an attenuation of 10% per cycle (1.6×10^6 sec^{-1}). We note that the amplitude spectrum is essentially featureless at frequencies well below the resonance frequency, which explains why the frequency about which a classical acoustic emission system is narrow banded is not critical. The piezo-electric detector crystal simply responds to the portion of this spectrum at or near its resonant frequency. If a specimen resonance rather than a crystal resonance is excited, the same argument holds. The detection transducer thus acts as a filter in the instrumentation system.

Ideally, to detect and record the subject pulse with good fidelity, a transducer with a flat frequency response from zero to perhaps 100 MHz should be used. Further, all components of the system should have a similar pass band. However, recall that the signal amplitude is expected to be very low and that an absolute restriction on the design of electronic instrumentation is the product of gain and bandwidth. Thus, we expect such a system to have a very high noise level. It is doubtful that a system could be designed with adequate sensitivity to record acoustic emission signals above the noise.

There are further difficulties of a mechanical nature connected with the proposed task. The acoustic emission signal must run through material to reach the transducer. This material and the specimen shape constitute another severe filter between the acoustic emission source and the readout device. The model signal will have specimen resonances superimposed on it. These arise from through-the-thickness reverberations, end-to-end reverberations, and ordinary spring-mass phenomena. The first two are subject to mode conversion as well. The complexity of such a filter for a simple tension specimen has been described in a report that attempted to infer the nature of the acoustic emission source with essentially classical instrumentation.(22) Unfortunately, equipment and signal processing limitations restricted accurate measurements to frequencies below 100 kHz in this effort.

A method of measurement and analysis that could possibly yield more meaningful information about the nature of the source acoustic emission pulse will be described. It would only be adequate for measurements of pulse samples, but even this could be useful from a fundamental research standpoint.

The proposed system would consist of at least two channels of acoustic emission instrumentation, narrow-banded about two rather widely separated frequencies and utilizing the resonant characteristics of two transducers. The frequencies might be 100 kHz and 1.5 MHz.

One would record data on the two transducers from a single acoustic emission pulse. The data could then be analyzed according to the method outlined in Ref. 22. Amplitude ratios of two portions of the pulse spectrum should aid in the analysis. Digital equipment is available which could possibly substitute for the laborious measurements from oscilloscope photographs described.

A few events which have been studied by acoustic emission techniques could possibly be recorded with reasonable fidelity. Two of these are breaking of strands in a filamentary composite and intermittent progression of a stable crack. In both cases, one would expect frequencies of the source event to be one or two orders of magnitude below that assumed for the model source. One would be aided in this case by the fact that the signal amplitude at the source would be larger than that assumed in the above discussion.

2.4 Limitations

Some limitations inherent in acoustic emission design will be summarized below. They are based on the low level of the source signal, its high frequency, and mechanical and electrical interference.

The choice of transducer is essentially limited to a properly chosen piezo-electric type. However, even with this type, it is difficult to operate in any mode other than that which capitalizes on the enhanced output of the transducer at resonance. If one seeks a high fidelity recording of the source signal and attempts to eliminate the filtering effect of the specimen by making it thin, problems of transducer response occur. This is because an acoustic emission source has a small extension in space. If the transducer were placed essentially in contact with it, the transducer would operate abnormally.

All published transducer sensitivities assume that the pressure over the sensitive face of the transducer is uniform at a given time. Mechanically, this implies that the transducer is excited in a one-dimensional stress mode. However, if the transducer is excited over only a small portion of its sensitive face, it will be operating in a more complicated mode, approaching one-dimensional strain for sufficiently short pulses. In such a case, its sensitivity characteristic should be reexamined. Thus, a piezo-transducer is non-ideal from both lack of flat frequency response and potential size problems.

The principal limitation for the rest of the electronic portion of the system is signal-to-noise ratio. This is the major consideration in selecting the first amplifier stage following the transducer. Fortunately, the state-of-the-art has largely caught up with this problem.

Important secondary considerations for a first-stage amplifier are ability to recover quickly from overloads and protection from burnout. The amplifier must be able to record signals at a 10-microvolt or so level. However, it could easily receive a signal of a hundred volts or more from a piezo-electric transducer coupled to it. Such a signal can ruin a field-effect transistor which is inadequately protected.

Acoustic emission systems must be operated near large loading mechanisms, which frequently leads to electrical interference problems. A testing machine, because of its size and because it is an electrical conductor, becomes an unwanted receptor of stray radio-frequency signals. Adequate shielding of the sensitive portion of the electronic system is difficult to achieve. Unfortunately, no panacea can be offered. Some skill, some luck, and intuition gained from experience must be combined with good cabling practice to overcome such difficulties as they appear.

The most common method of inducing acoustic emission in a specimen is mechanical loading. Frequently, the mechanical loader must produce large forces. Demountable connections must be designed to get the test specimen into and out of the machine. Great care must be taken to ensure that artifact signals are not produced in grips, other accessories, or the machine itself. For example, one of the most modern servo-hydraulic testing machines available is almost unusable as a loader for acoustic emission tests. The source of the noise in this machine is in the cavitating hydraulic fluid in the narrow channels of the load piston and cylinder, and the high frequency content is rather intimately coupled to the specimen.

While the limitations discussed above are by no means exhaustive in their scope, they should serve as a warning to the uninitiated that designing an acoustic emission system contains many subtle pitfalls. Failure to observe proper precautions will lead to instant acquistion of data—all fallacious.

3. MATERIAL EVALUATION

3.1 Metals

Acoustic emission from metals is generally associated with dislocation motion accompanying plastic deformation. Several investigators(20,23,24) have obtained correlations between number of acoustic emission events and strain. These correlations indicate that the smallest detectable event involves collective movement of 5-150 dislocations. Hence, acoustic emission analysis is applicable to studies of plastic deformation processes in metals which involve the motion of sufficient dislocations to provide pulses of detectable magnitude.

Generally speaking, more acoustic emission is observed from high-strength brittle materials, which is consistent with the higher energy levels associated with dislocation pileup and breakaway in these materials. Another aspect of the relationship between plastic deformation and acoustic emission is their common irreversibility. That is, if a material is loaded to a given stress level and unloaded, no emission will be observed during subsequent loading until this level has been exceeded. This phenomenon, known as the Kaiser effect,(8) has been observed by numerous investigators.

The irreversibility has important practical implications since it can be used to detect subcritical crack growth, as will be discussed later. It can also be used to develop passive peak pressure and acceleration transducers.(25)

Unflawed Specimens. Acoustic emission from initially flaw-free metal specimens generally consists of two components:

(1) Low-level continuous - This component of the acoustic emission usually occurs continuously. On an oscilloscope, it appears very much like background electrical noise. It is associated with plastic deformation occurring at relatively small plastic strain. This component increases in amplitude as the load is applied during a rising load tensile test, and appears as a growth of

noise. This component decreases with increasing strain after yielding occurs, and is replaced by the second component near failure.

(2) High-level burst - This component does not occur continuously, but in bursts. It is usually of higher amplitude than the continuous emission component, and is associated with the twinning and micro-crack formation that occur at large plastic strains.

Results from a metal tensile specimen are presented in Fig. 1, which shows the acoustic emission count rate as a function of strain on the tensile specimen. The peak in the count rate at strains near yielding is typical of the results obtained from metals,(24,26,27) and is consistent with the observation noted above that the continuous emission component decreases as straining is continued beyond yielding This figure also shows a fit of Gilman's equation(28) for mobile dislocation density as a function of plastic strain. The excellent fit of Gilman's equation to the acoustic emission results is further evidence of the close association between acoustic emission and the dislocation movement accompanying plastic deformation in metals.

Time-dependent <u>creep</u> deformations have been characterized with acoustic emission techniques. Tertiary creep processes were studied in "40-60" solder wire, and it was reported that acoustic emission activity continuously increased from the time the constant load was applied until failure.(13)

"Delayed" acoustic emissions (emissions generated at constant stress) were studied by Adams et al.(29) Generally, only primary creep processes are operative at T/T_m ratios of 0.25 or less. In hexagonal close-packed metals, most low-temperature creep is controlled by dislocation interactions. These mechanisms predict log-time and exponential stress laws to characterize the creep behavior. From experimental studies of beryllium at room temperature ($T/T_m \sim 0.20$), the acoustic emission rate $\dot{N}$ at constant stress was reported to be

$$\dot{N} = Dt^{M} e^{B\sigma} \qquad (5)$$

where D, B, and M are constants, t is time, and σ is the applied tensile stress. At stresses near yield, emission activity sometimes continued for hours and appeared to decay to a steady-state value. The results indicate that emission rate is proportional to the creep strain-rate and that summation of emission activity is proportional to creep strain.

Results similar to those for beryllium were noted in studies of zinc at room temperature.(30) However, in addition to primary creep processes, secondary or steady-state creep mechanisms were operative. The emission rate at constant load decayed to a constant level which was reached when the creep strain-rate decreased to a steady-state value.

Acoustic emissions have been noted during the three stages of creep: Primary; steady-state; and tertiary. Although only limited work has been accomplished in this area, it appears that characterization of creep behavior by acoustic emission techniques can be of considerable value.

The relaxation of residual stresses under no external load is accompanied by dislocation motion, so acoustic emission analysis should also be applicable to studies in this area. Some preliminary studies conducted at Lawrence Radiation Laboratory on freshly machined beryllium resulted in essentially no acoustic emission being detected. This does not preclude the applicability of acoustic emission techniques to such studies, however, and emission should be observed when enough energy is released by the relaxation processes in a sufficiently short time period.

Flawed Specimens. Acoustic emission has proved especially useful for detecting cracks and other flaws. Flaws act as stress concentrators to cause localized plastic deformation at nominal stress levels well below general yielding. As acoustic emission is associated with plastic deformation, it can be used to detect such flaws and to provide information on the integrity of engineering structures. Basic studies on cracked specimens will now be discussed; actual applications to structural integrity evaluation will be covered in a later section.

The acoustic emission from a cracked specimen during a rising load test has been extensively studied,(26,31-33) and fracture mechanics concepts have been used to analyze the results.

The stresses near the tip of a crack in an elastic solid are completely controlled by the stress intensity factor K.(34) If plastic deformation is highly localized near the crack tip, the plastic zone size will also be controlled by K.(35) Hence, the acoustic emission will also be K-dependent.

A model to predict the relation between the acoustic emission from a flawed specimen and the stress intensity factor for the crack has been proposed.(26) This model predicts that the summation of acoustic emission is proportional to the fourth power of the stress intensity factor (for through cracks in plates):

$$\Sigma N \propto K^4 \qquad (6)$$

This shows that it is possible to relate the number of acoustic emission counts for a given load directly to the stress intensity factor for the crack at that load. This is very important since it is actually the stress intensity factor, rather than the flaw size itself, that controls the onset of rapid crack propagation.(36,37)

The strong dependence of acoustic emission on K in the above equation indicates that, when more than one flaw is present, the flaw with the largest K will contribute the majority of the emission, and less severe flaws will have only a secondary effect. The acoustic emission from surface and embedded flaws cannot be directly related to K, but must be referred to the flaw size or stress level.(33)

In actual situations, the exponent in the acoustic emission-stress intensity factor relation has usually not been 4. It varies from 4 for some 7075-T6 specimens(33) to about 8 for beryllium.(26) Figures 3 and 4 show acoustic emission results from four 1.5-in. wide, 0.10-in. thick single-edge-notch fracture toughness specimens of 7075-T6 aluminum with fatigue cracks of various lengths. These curves show that the stress intensity factor is the parameter controlling acoustic emission, as expected. The exponent for this material and thickness was 4, the value predicted from the model.

Tests were also conducted on 0.40-in. thick, 2.25-in. wide 7075-T6 specimens containing fatigue cracks in various locations. These tests were performed to determine the effects of multiple flaws and geometries other than single-edge-notch on emission. The results are presented in Figs. 5 and 6, which show that K is again the controlling parameter and that emission was not appreciably altered by the presence of multiple flaws. The exponent in the N-K relation was found to be 5.4 for this material and thickness.

The disagreement between the theoretically predicted exponent of 4 and the results of actual tests could be caused by several factors. Some possible causes are the presence of twinning (which occurred near the crack tip in beryllium) and the microcrack formation and crack tunneling (pop-in) which occurred in aluminum. These factors would tend to give a higher exponent than that predicted because they occur in addition to the plastic deformation considered in the model.

Acoustic emission has also been utilized in the detection of "pop-in"(36,37) during a rising load fracture toughness test. In fact, the earliest studies of acoustic emission from flawed materials were concerned with detection of this phenomenon,(44,45) which only requires relatively insensitive equipment as pop-in is usually quite noisy. Typical results of an acoustically monitored fracture toughness test accompanied by pop-in are presented in Fig. 7, which shows the acoustic emission and notch-opening displacement measurements on a fatigue cracked single-edge-notched fracture toughness specimen of 7075-T6 aluminum. These curves show that the beginning of acoustic emission is associated with the slight change in slope of the load-displacement curve that occurs at a load of about 5000 pounds. A rapid jump in displacement occurred at about 7000 pounds, and was accompanied by considerable acoustic emission. The corresponding K_{Ic} value of 30.6 ksi-(in.)$^{1/2}$ agrees well with the results of numerous other investigators. This result shows that acoustic emission techniques are well suited for detecting pop-in.

Gerberich and Hartbower(38-40) have related the acoustic emission associated with pop-in to the new crack area developed as a result of crack extension. They have found the following quantitative relationship for a wide variety of materials.

$$\Delta A \propto (\Sigma g)^2 \, E/K^2 \qquad (7)$$

where ΔA is the incremental area swept out by the crack, Σg is the sum of the stress wave amplitudes associated with that increment of growth, E is the elastic modulus, and K the applied stress intensity factor. This relation has also been found to hold for subcritical crack growth caused by stress corrosion cracking. Thus, we see that acoustic emission can be used for quantitative measurements of crack growth during rising and constant load tests.

The fatigue crack growth produced by fluctuating loads can be detected by continuous monitoring of acoustic emission. Hartbower et al(41) have investigated the acoustic emission during low cycle fatigue from D6Ac steel with various heat treatments. Their results are presented in Fig. 8, where Σg is the summation of the amplitudes of the emission pulses. This figure shows that it is possible to detect the growth of fatigue cracks by continuous monitoring, and that the amount of crack growth per cycle can be directly determined from the acoustic emission data. However, the amount of emission for an increment of crack growth depends on both the material and its previous history such as heat treatment. The curves of Fig. 8 indicate that the amount of emission per cycle greatly decreases at low crack growth rates, and that the crack growth rate associated with high cycle fatigue (~1 μ in./cycle) may be below the detection threshold of the instrumentation. Continuously monitoring structures subjected to a large number of fatigue cycles is often inconvenient, so in most cases it would be more satisfactory to apply intermittent overstressing with simultaneous monitoring for acoustic emission to detect growth of fatigue cracks. This intermittent overstressing technique will be fully described in the section on evaluation of structural integrity.

Acoustic emission analysis has also been applied to detection of subcritical crack growth, which is the extension of cracks at K levels below that required for rapid crack propagation. In addition to fatigue, subcritical growth can result from stress corrosion cracking and hydrogen embrittlement,(42) and is accompanied by elastic strain energy release and plastic deformation. Acoustic emission analysis has proven to be a very sensitive tool for detecting subcritical flaw growth, and its applicability to the detection of hydrogen-induced crack growth and stress corrosion cracking has been thoroughly demonstrated.(33,38,39,43)

Figure 9 presents the results of a stress corrosion test on a fatigue pre-cracked uranium-0.3% titanium specimen in salt water(33) which was conducted under nearly fixed-grip conditions. This figure shows the emission observed as the load was being applied, the relatively little emission and stress intensity factor decrease before the salt water was added, and the greatly increased activity accompanying crack extension immediately following the addition of salt water. The stress intensity factor decreased as the crack grew, with resulting decreases in the crack growth rate and acoustic emission activity.

Similar studies on the acoustic emission characteristics of hydrogen-induced crack growth(43) have demonstrated the applicability of acoustic emission techniques to prediction of impending failure. In summary, it has been found that acoustic emission is a very sensitive indicator of subcritical flaw growth. It provides a potentially powerful tool for early detection of flaw growth, and should prove useful in combatting this troublesome cause of numerous service failures.

3.2 Composite Materials

Applications. The renewed interest in composite materials during the past decade is evident in the increasing number of papers, articles, and reports written on the subject every year. Man's desire to design materials for various applications is perhaps nearly realized in design of composite materials where predicted quantitative properties result from knowledge of the intrinsic properties of the constituent materials.

The definition of a composite material given by Krock and Broutman(46) requires that the following criteria be met: The composite material must be man-made; the composite material must be a combination of at least two chemically distinct materials with a distinct interface separating the components; the separate materials forming the composite must be combined three-dimensionally; and the composite material should be created to obtain properties which would not be achieved by any of the components acting alone.

Composites can be classified into one of three categories, on the basis of microstructure:

(1) Dispersioned-strengthened

(2) Particle-reinforced

(3) Fiber-reinforced

Quite different criteria are used to interpret their mechanical properties.

Acoustic emission from composite materials can be generated in a variety of ways during the straining of a composite material: Plastic deformation or fracture of the matrix; plastic deformation or fracture of the second phase (usually harder than the matrix); or failure of the interface between the matrix and second phase.

The following sections will attempt to characterize composite materials during straining by acoustic emission techniques. Each class of composite will be discussed individually.

The class of dispersion-strengthened composites is characterized by a microstructure having an elemental or alloy matrix within which fine particles of 0.01- to 0.1-μin. diameter are uniformly dispersed in a volume concentration of 1 to 15%. The matrix acts as the principle load-bearing constituent. The dispersed phase impedes dislocation motion (slip), thus work-hardening the matrix. The rate of work hardening depends on particle size and shape. The prime variable for determining dispersion effectiveness is the mean free path between particles.

Honeycombe(47) discusses the theories of work-hardening of metals and of deformation of crystals containing a second phase in terms of the interaction of dislocations with second phase particles. These dislocations either cut through the dispersed particles or take a path around the obstacles. The stresses at the leading dislocation in a pileup are reported to be equal to the stress times the number of dislocations in the pileup. As indicated in the section discussing acoustic emission from metals, when the driving stress on the leading dislocation (applied stress plus stress concentration due to pileup) is large enough to cause breakaway and acceleration of part of the group, the local strain energy relaxes rapidly and excites lattice vibrations or acoustic emissions.

We conjecture that the emission activity generated during straining of a dispersion-strengthened composite will be of a continuous low-level nature rather than burst-type. Results similar to those for 7075-T6, a precipitation-hardenable alloy of aluminum (Fig. 1) are expected from dispersion composites.

Particle-reinforced composites differ from dispersion composites in that the particle size exceeds 1.0 μ and the concentration generally exceeds 25%. In this class of composites, matrix and dispersed particles share the load and strengthening occurs initially when the dispersed particles mechanically restrain matrix deformation, a very complex reaction. The particle phase deforms plastically in ductile composites and provides hardening in brittle composites.

The acoustic emission response during straining of a particle composite probably depends on plastic deformation of the particles themselves before fracture. When the particles do not deform plastically before fracture, a situation on emission response similar to that of a dispersion composite is envisioned. If the particles deform plastically, the possibility of a double peak of emission activity exists, with one peak related to the matrix and the other related to the particle phase.

The distinguishing microstructural feature of fiber-reinforced composites is the one long dimension of their reinforcement. Hence, the properties are a great deal more anisotropic than the two other classes of composite materials. Here the main purposes of the matrix are transmitting the load to the fibers and spacing the fibers. The fibers are the principal load-bearing constituent and range in size from a fraction of a micron to several mils in diameter. Volume concentrations range from a few percent to greater than 70%. Fiber composites are used for tailor-made properties; applications generally require a high strength-to-weight ratio. Fiber materials include whiskers, metals, glass, ceramic, and polymer materials.

Low-level acoustic emissions can be generated by the plastic deformation of the matrix or the fibers. However, burst-type emissions are usually predominant during straining to failure. Sources of this high-level activity are fiber failure, matrix cracking, and interface failure or fiber pullout.

Tensile Tests. Most theories of tensile failure of fiber-reinforced epoxies consider only the strength properties of the glass.(48,49) Experimental work by Zweben(49) supports a cumulative fracture-propagation concept. Figure 10 represents results of experiments on specimens consisting of a planar array of glass fibers embedded in an epoxy matrix. The theoretical prediction is represented by a dashed line in Fig. 10. It was shown that scattered fiber breaks occur at less than 50% of the ultimate load. As the load increases, an increasing number of random breaks appear throughout the specimens. Considering the statistical spread in fiber properties, this is fairly good agreement between experimental and theoretical predictions.

Tests were conducted on filament-wound Naval Ordnance Laboratory (NOL) rings of "S-type" fiberglass with an epoxy resin matrix. The rings were loaded in tension by a split-ring assembly and acoustic emission data obtained. Fiber failure was the emission generator in this case. Summation of emission as a function of load for an NOL ring is shown in Fig. 11; the experimental evidence supports the cumulative-damage theory. Compression tests on 1-in. cylinders of matted fiberglass-epoxy having the compression axis perpendicular to the plane of the woven fiberglass showed very similar results. The fracture plane on these specimens was 45° to the compression axis.

Acoustic emission techniques for assessing the extent of microfracturing during straining of fiber composites have proven very useful. They are easily adaptable to simple or very complex structures, are relatively inexpensive, and have only limited data acquisition time. Analysis of data is helpful in establishing the mechanisms governing the operative fracture modes. Acoustic emission can be readily used to assess the structural integrity of fiber composites which have been strained in unusual ways to create complex stress distributions.

Acoustic emission has been monitored during tensile tests conducted on whisker-reinforced metals. Flat tensile specimens of unidirectionally solidified $Al-Al_3Ni$ eutectic alloy having whiskers aligned with the tensile axis were pulled to failure while being simultaneously monitored for acoustic emission.(50) The results of the test are presented in Fig. 12, which shows that acoustic emission occurred in a sporadic manner, but tended to increase in a linear fashion with strain. The acoustic emission from this material is thought to be primarily caused by whisker breaking. It is possible to develop a model relating emission to applied tensile strain.

The percentage of broken fibers as a function of the applied tensile strain was measured optically(50) during tests conducted at several different temperatures. Figure 13 presents the room temperature results, which provided the first step in the model development. An emission-strain relation can be obtained by assuming that the whiskers are always elastic, that the strain in the whiskers is equal to the strain in the matrix, that all acoustic emission comes from whisker breakage, and that the number of counts produced by a break is proportional to the square of the whisker stress. If $\omega(\epsilon)$ is the percentage of broken whiskers (Fig. 13), the above assumptions give an incremental count of:

$$dN(\epsilon) \propto \sigma_f^2 \, d\omega(\epsilon) \tag{8}$$

Introducing the proportionality constant C' and noting that $\sigma_f = E_f \epsilon_f$ and $\epsilon_f = \epsilon$ according to the above assumptions, this equation can be rewritten as:

$$dN(\epsilon) = C' E_f^2 \epsilon^2 \, d\omega(\epsilon) = C \epsilon^2 \frac{d\omega(\epsilon)}{d\epsilon} \, d\epsilon \tag{9}$$

where $C = C' E_f$. This is an ordinary differential equation, which can be integrated as follows to give the functional relationship between N and ϵ.

$$N(\epsilon) = \int_0^N dN = C \int_0^\epsilon x^2 \frac{d\omega(x)}{dx} \, dx \tag{10}$$

The function $\omega(\epsilon)$ can be curve-fitted from the data of Fig. 13. It can then be differentiated and inserted into Eq. (10) to provide an ordinary first-order differential equation which can be solved for the functional relationship between N and ϵ. The results of such calculations are presented in Fig. 12, where the constant C was adjusted to force the experimental and theoretical results to agree at a strain of 1.5%. The theoretical and experimental results agree fairly well, considering that the abrupt jumps in the experimental data (such as observed at a strain of 0.85%) cannot be predicted from the smooth variation of ω with ϵ.

These results show that acoustic emission analysis is well suited to the study of the deformation characteristics of metal composites, and that it is possible to correlate the emission behavior with independent observations of the behavior of the material. Acoustic emission provides information on the bulk deformation properties of the material, which are often more reliable and less tedious to obtain than is information obtained from microscopic examination of the specimen surface.

Fatigue Tests. Poor resistance to cyclic mechanical fatigue is one factor limiting the usefulness of fiber-reinforced composites. In glass-resin systems, degrading effects arise from initiation and propagation of small cracks in the resin phase, where local high stress concentrations produce small cohesive failures. As the microcracks multiply and grow in size, the structural integrity of the material is reduced, stiffness and strength properties diminish, Poisson's ratio declines, resistance to water and general chemical attack diminishes, and optical and electrical behavior usually deteriorate.

McGarry(51) reports that cracking increases with applied stress level and the number of cycles imposed; however, a disproportionate amount of damage occurs during the first cycle. The cracking results primarily from a combination of resin brittleness, fiber-fiber contact or proximity, and tensile stress components acting perpendicular to fiber bundles.

Acoustic emission techniques are very sensitive to resin cracking and fiber failure. NOL rings (fiberglass and epoxy resin) were cycled at approximately one-half of their ultimate load and intermittently proof-tested to three-fourths of their ultimate load. During the proof cycles, microfracturing activity was monitored by acoustic emission techniques. The results, shown in Fig. 14, indicate that microfracturing activity or acoustic emission activity increases with number of fatigue cycles. This type of analysis (emission monitoring during proof cycling) could be readily applied to complex structures or to evaluation of composite material or part degradation during service life.

3.3. Geologic Materials

Bieniawski(52-54) discusses the various mechanisms of brittle fracture of rock in tension and compression and takes into account the significant failure processes from initial load application to complete failure. His approach describing the fracture mechanisms of rock is shown in Fig. 15. Studies of the mechanical properties of geologic materials are often complicated by the anisotropic and inhomogeneous qualities of rocks. Because of the transient nature of the mechanistic processes involved in deforming and fracturing rocks, studies of the strain behavior by acoustic emission techniques are particularly appropriate. The deformation and fracture process (Fig. 15), from the movement of cracks upon initial stress application to the final rupture mechanism, is ideally suited to acoustic emission analysis. Each involves a transient process which is a known generator of emission activity.

In recent years, many studies of mechanical properties have turned from homogeneous-isotropic assumptions to a defect approach, similar to the concepts of fracture toughness so successfully applied to metals that fracture in a brittle manner. This approach appears very reasonable since the defect density of most rocks is high and many types of defects are present. Examples of defects on a macroscopic level are cracks, pores, impurities, multiphases, and jointed and folded surfaces.

Elastic shock, elastic radiation, rock noise, microseismic activity, and seismo-acoustical activity are terms that have been used to describe the transient vibrations or acoustic emissions generated during the straining of rocks.

Rockbursts are sudden explosive failures of coal seams or mine walls. The desirability of acoustic detection techniques was appreciated at an early date; however, little progress has been made toward a solution of the rockburst prediction problem, despite the accumulation of a very large quantity of acoustic data. As early as 1923, Hodgson(55) proposed the use of subaudible noises in the prediction of earthquakes and rockbursts. In Russia, great effort has been directed to finding a reliable method of detecting imminent rockbursts, primarily through seismo-acoustical studies of deep-level coal seams.(56) Similar investigations have been made in the United States,(57-59) Japan,(60) South Africa,(61) and Sweden.(62)

Knill, Franklin, and Malone(63) discuss the results of previous investigations which are relevant to the study of rock mechanics. They conclude that acoustic emission observation is a useful tool for studying material behavior and that the technique has considerable research potential in rock mechanics.

Investigators at Pennsylvania State University are conducting extensive studies associated with emission activity and inelastic behavior of geologic material. Brown and Singh(64) showed that the main mechanism of emission activity in their tension tests of various rocks was the propagation of small cracks through and between rock grains. Later experiments by Hardy and his associates(65-67) revealed that the accumulated emission activity vs. time in most experiments fit the generalized Burgers model for creep and that a linear relationship existed between accumulated emission activity and axial creep strain. The frequency spectrum of emission activity was not found to be a fundamental parameter. It is concluded that inelastic strain during rock deformation results from microfracturing within the rock.

The influence of microfracturing on the stress-strain behavior of brittle rocks was studied by Scholz.(68-70) A significant feature of the experimental work was that the frequency range of 100 kHz to 1 MHz was analyzed. Most other studies of emission activity in rock samples have been limited to the audible range or much below. It was reported that the time-independent inelastic stress-strain behavior of brittle rocks could be completely accounted for by the strain released during microfracturing. Also, it was indicated that rock deformation in laboratory experiments could be related to earthquakes according to the Gutenberg-Richter relation and that the rock type and the state of stress could be reflected in the constants of the relation. Ikegami's(71) studies of the magnitude-frequency relation of earthquakes during a 40-year period supported Scholz's work by noting that periods of great seismic energy release correspond to periods during which one of the constants in the Gutenberg-Richter relation is a minimum.

Mogi(72,73) demonstrated that the statistical behavior of microfracturing activity observed in laboratory experiments is in many ways similar to that observed for earthquakes. In addition to observing the similarity of the frequency-magnitude relations, he showed that the buildup of activity preceding fracture in laboratory tests is similar to the earthquake foreshock sequence. He reproduced foreshock and aftershock sequences in models by relating the stochastic process of microfracturing to the degree of heterogeneity of rock samples. He noted that laboratory experiments on fracture suggest the possibility of earthquake prediction by measurements of anomalous strain increases and foreshocks.

Armstrong(74) explored the hypothesis that animal agitation just prior to earthquakes is caused by high-frequency sound emission from preliminary fracturing. He discusses generation of acoustic emission in earth materials and propagation and detection of acoustic waves in various materials, and suggests that, under certain conditions, high frequency emission may be detected from highly strained regions prior to earthquakes.

To assess the usefulness of applying emission techniques to studies of the strain and fracture characteristics of rocks, several preliminary experiments were conducted at Lawrence Radiation Laboratory. A specimen of Sturdevant Quartzite was strained in compression to failure at a confining pressure of 3.5 kbar. The stress-strain curve for this material is essentially linear to failure at atmospheric pressure. At high confining pressures, stick-slip processes become operative. Figure 16 shows that acoustic emission techniques are very sensitive to stick-slip processes. The data show that dissipative energy-release process operates prior to all stick-slips. The stress-strain relation for the sample shown in Fig. 16 would consist generally of linear elastic portions followed by a stick-slip. The emission data demonstrate the operation of an energy-dissipating mechanism prior to each stick-slip.

In tilting plane experiments for determining the coefficient of friction for an aluminum alloy, Tatro and Liptai reported(75) that acoustic emission activity builds to a maximum at an angle of five degrees and then declines, whereas sliding occurs at slightly less than fifteen degrees. These experiments suggest that acoustic emission techniques can be applied to investigations of the mechanistic processes of friction. Both current theories of friction, plastic deformation and adhesion and brittle failure of asperities, are appropriate for acoustic emission analysis. It seems reasonable that results of laboratory studies may be extended to apply to seismic activity, particularly micro-earthquake phenomena.

Acoustic emission monitoring was used on experiments designed to establish the shear strength of rocks to 70 kbars.(76) The apparatus developed by Abey and Stromberg(77) to shear bulk materials under very high pressure was used. Acoustic emission data provided clearer understanding of the deformation mechanisms operative at high pressures.

Acoustic emission techniques have a very wide application in the field of rock mechanics. Although only a limited amount of work has been accomplished in this area, emission analysis holds great promise as a research tool and as a technique for various practical applications.

4. STRUCTURAL INTEGRITY EVALUATION

Assurance of structural integrity requires extensive nondestructive testing at various points in the fabrication process, up to and including a final proof test. Such nondestructive inspection techniques as radiography, visual inspection with penetrants, ultrasonics, and eddy-current measurements are generally time consuming and expensive, and are often inadequate because of low resolution or operator error.

Flaws that affect the integrity of fabricated structure arise from four basic sources: Flaws in the basic material; flaws introduced by forming processes; flaws introduced by joining processes; and flaws that become critical as a result of slow crack growth due to fatigue, stress corrosion, or embrittlement.

Catastrophic failure during proof test has so many ramifications that nearly any technique of reducing the probability of such failures (such as improved fabrication methods) or of detecting or locating critical defects during proof testing (in time to terminate the test and make appropriate repairs) will be economically desirable. Present acoustic emission technology offers this capability.

4.1 Joining Processes

Many critical flaws in structures arise from improper joining techniques. If these are eliminated or prevented early in the fabrication process, repair time required later in the fabrication process will be saved.

Acoustic emission was first applied to welding technology by Notvest in 1965.(78) He used detection apparatus which was "sensitive enough to detect the austenite-to-martensite transformation when in a quiet environment" to detect "acoustic waves originating from crack events" in restrained joint cracking tests of welds in D6Ac steel. Notvest was able to establish a thermal treatment of preheat and postheat that produced no acoustic emission and that was applied to the weld fabrication of Titan II 120-in. diameter rocket motor cases with reduced in-process weld cracking and fabrication costs.

Day(79) and Jolly(80-83) report successful application to in-process weld inspection. Hartbower has successfully monitored weld joints in HY80 and HY150 steels to detect cracking during cooling and delayed slow crack growth with aging.(84)

Acoustic emission was found to be a reliable indication of adhesive bond strength by Schmitz and Frank(85) and Beal.(86) Muenow reports(87) the utilization of acoustic emission to determine the approximate location of regions of nonbond in large laminated wood beams. Suspect areas are then examined radiographically or with low frequency ultrasonics to ascertain the size of the nonbond area. This technique eliminates the need for complete examination by radiographic or ultrasonic techniques, with a significant cost savings as a result.

4.2 Proof Testing of Pressure Vessels

The greatest effort expended has been in developing techniques for application to the evaluation of pressure vessels during proof test. The earliest study was made by Green et al.(88,89) to evaluate the integrity of filament-wound chambers for Polaris in 1962-63. The success of this program led to a proposal to investigate the applicability of their STRESS-WAVE-ANALYSIS-TECHNIQUE (SWAT) to prevent failures during hydro-test of 260-in. diameter motor cases. This work demonstrated that the acoustic emission phenomenon provides a practical signal for terminating proof tests before catastrophic failure(90,91) and for locating the failure point by triangulation techniques.(92)

Subsequent applications to proof tests of a Saturn II aft-LOX bulkhead made of 2014-T6 welded aluminum alloy,(93) LEM ascent tanks of Ti-6Al-4V alloy,(94,95) and a 260-in. diameter SL-2 chamber(96) were made. They resulted in the suggestion by Hartbower and Crimmins that application of acoustic emission techniques was essential to preventing unexpected catastrophic failure of pressure vessels from slow crack growth during proof test. They cite(96) five different vessels for a total of 19 failures that probably could have been prevented with proper utilization of acoustic emission. The situations are worth repeating.

(1) A catastrophic brittle failure during a routine air-leak test of a large steel pressure vessel at 3200 psig after two successful

7500 psig hydrostatic tests. The failure was probably caused by hydrogen embrittlement during processing between the last hydrotest and the leak test.(97)

(2) Two 42-in. diameter rocket motor cases for the second stage of Minuteman and four 52-in. diameter second stage Minuteman chambers made of 6Al-4V-titanium failed during hold at proof pressure or in the case of one of the 42-in. diameter cases during rising load after a few cycles to higher load.

(3) Six of ten Polaris chambers were investigated. It was concluded that failure of four, and probably the other two as well, was caused by stress corrosion cracking and temper embrittlement. The material was AISI4335 V Steel.(98)

(4) A Saturn S-II liquid hydrogen tank (CBTT) made of 2014-T6 aluminum failed on December 1, 1966. The investigation(99) concluded that failure was due to either an unknown flaw that was undetected or an unknown low-cycle high-stress life cycle limit that was exceeded. Slow crack growth as the result of stress corrosion cracking in water is advanced by Hartbower and Crimmins as a third possibility that was not discussed.

(5) A 260-in. SL-1 motor case made from air-melted grade -250, 18% nickel maraging steel failed from an undetected flaw.(92) This was critical at 56% of the anticipated proof pressure. An early SWAT System was on board for this test and was able to locate the failure source by triangulation after the test. Subsequent tests on an SL-2 motor case were made to assist with the evaluation of chamber integrity. This vessel was passed and has withstood two successful test firings and a second hydro-test.(41)

Acoustic monitoring techniques have also been applied to 10-in. glass hemispheres and spheres under hydrostatic compression.(100,101)

Later applications to pressure vessel proof testing include a successful feasibility study on testing propellant tankage in situ at Kennedy Space Center(102) and some preliminary exploration in evaluating prestressed concrete vessels for Oak Ridge.(103)

In early 1966, Hutton and Parry began to develop techniques to apply acoustic emission analysis to the problems of nondestructive testing of assembled reactor pressure vessels and primary pressure system components in nuclear power plants. Their common goal is to provide integrity analysis by detecting, locating, and describing incipient failure conditions in operating plants.

Some early work consisted of investigations of pressure piping with acoustic emission instrumentation to determine if known flaws could be detected. This work has progressed to situations simulating more difficult field problems such as acoustic emission crack detection in the presence of hydraulic noise(104) and crack detection in the presence of simulated reactor noise.(105) Other research has been directed to characterizing emission from sources and materials likely to be encountered in reactor systems and to developing the technique of separating acoustic emission signals from those caused by cavitation, boiling, and mechanical noise present in operating reactor systems.(106)

Hutton characterizes the state-of-the-art as being reliable for detecting and locating flaw growth in pressure vessels undergoing hydrostatic test and for surveying local areas of known high potential for flaw growth (i.e., piping connections in the primary coolant systems in an operating system). He indicates that the resolution attainable in detecting flaws appears to significantly exceed that of any conventional NDT technique.

The task of applying detection techniques to complex nuclear power systems was investigated by Parry and Robinson.(108) They have used multi-channel data acquisition with computer assistance to triangulate emission sources in large pressure vessels. Parry states that the Incipient Flaw Detection System (IFDS) developed since 1966 has proven capable of rapidly detecting and locating flaws during hydrostatic acceptance and requalification testing of nuclear reactor pressure vessels. The system has been successfully used to locate leaks in the large primary system of the nuclear power plant at Elk River and to provide integrity analysis of several large pressure vessels.

The present IFDS system is capable of locating emission sources to within one wall thickness with sensitivity adequate to detect any significant flaw during hydrostatic testing. Attempts to detect emission from unsuspected sources during operation of nuclear power plants with the present IFDS system indicate that much refinement of signal processing will be required if continuous in-service monitoring in the presence of high background noise is to be accomplished.

Hutton has been successful in monitoring acoustic emission from known flaws in the low MHz band in the presence of simulated reactor noise.(108)

The groups primarily interested in applications to pressure vessels agree that they can detect flaws much smaller than those detectable by any other NDT technique.

Aerojet General usually couples its proof testing efforts with a study of the relation between crack propagation and acoustic emission of the material from which the vessel is made. This allows adjustment of the detection level so that relatively few stress wave (acoustic) emissions are accepted for triangulation. This is necessary in order to use a small computer with limited capacity for on-line real-time location and display. Idaho Nuclear, on the other hand, uses a higher detection sensitivity and stores emission counts by arrival time differences until appreciable activity is noticed for the arrival time sequence from a possible source. The lumped data are used for triangulation. As a result, the IFDS system finds many more flaws that are insignificant to vessel integrity than does SWAT.

Idaho Nuclear has tested several large vessels and has found enough flaws, which were confirmed by detailed inspection to be of no consequence to vessel integrity, to indicate that all flaws which might affect vessel integrity will be found.

Esso Research and Engineering Co. is developing a system of their own for detection and location of defects in large pressure vessels during hydro-test. Their experience with four large vessels tested for them by Parry has been that about 75% of the sources indicated by the IFDS system have been verified to be non-critical.(107)

4.3 Detection of Flaw Growth Against High Background

General Dynamics became active in acoustic emission in September 1968.(109) Their goal was development of a system capable of detecting initiation and growth of cracks in aircraft components and structures during fatigue cycling. Riveted and bolted structures obviously presented unique background noise problems and their efforts, once they determined that they could detect initiation and growth of fatigue cracks, have been concentrated on developing this system to discriminate between normal friction emission from fasteners and that from fatigue cracks.

This system, which has been developed considerably in the last year and a half, presently has the following limitations:

(1) Noise sources (i.e., rubbing components) close to regions of interest can completely mask the desired emission signal.

(2) One array covers only about 1 cubic foot, and only 10 arrays can be handled.

(3) Master sensors must be skillfully mounted close (within 1 foot) to suspect locations.

(4) No universal method is yet available for predicting catastrophic failure.

General Dynamics' system differs from SWAT and IFDS because of the large number of non-flaw emission sources present in riveted and bolted structures. Because of this physical reality, they utilize a few master detectors located in the area of interest and surrounded by a ring of slave transducers. They save for analysis and location only those signals detected by <u>all</u> master transducers before <u>any</u> slave transducer detects the event. This effectively shields against emission or noise coming from other areas and has a rejection ratio of 30,000 to 1. However, it requires large numbers of transducers.

Balderston uses signature analysis to evaluate bearing damage and hydraulic component wear in running jet engines. He suggests that there are frequency bands with sufficient contribution to the power spectrum from acoustic emission to allow emission detection in the presence of high background.(110) This approach will require extensive investigation and very narrow-band transducers. In operating nuclear plants, boiling and cavitation will continue to produce confusing signals since they seem to be as broad in their spectra as are acoustic emission signals.

Anderson and Gate are working on acoustic boiling detecting systems for reactor application.(111)

4.4 Integrity Evaluation by Periodic Overload

Techniques for detecting subcritical flaw growth are of great technological importance for combatting this all-too-common cause of structural failure. The application of acoustic emission to the detection of subcritical growth (regardless of cause) by continuous monitoring of the structure has already been discussed. However, continuous monitoring is often impractical, because of expense involved and excessively high background noise during service.

A technique based on intermittent monitoring during a periodic overload (proof test) has been developed which can overcome some of the disadvantages associated with continuous monitoring.(112-114) This technique can be applied regardless of the mechanism of crack growth, but only the case of fatigue has been considered in tests conducted to date. The extension of the technique of other mechanisms of crack growth is very straightforward. The intermittent overload technique is based on the irreversibility of acoustic emission that was discussed earlier.

If a cracked structure is loaded to a particular value of K and then unloaded, emission will not occur again until this previous K value is exceeded. It is possible to take advantage of this irreversible nature to determine whether or not a crack has grown during cyclic loading at a stress σ_w, by periodically overstressing (proof testing) the structure at a stress σ_p ($>\sigma_w$) and monitoring for acoustic emission. If flaws have grown at σ_w since the previous overstress, the stress intensity factor during proof testing ($K_p \simeq \sigma_p (\pi a)^{1/2}$) will have increased, and emission will be observed during the proof test. Alternatively, if no crack growth occurred at σ_w, K_p would remain the same as during the previous proof test, and no new plastic deformation (hence, no acoustic emission) would occur.

A model to analytically predict the number of acoustic emission counts N_t observed during the proof test as a function of the number of fatigue cycles n at the working stress has been presented(113,114) for a crack of known initial size in any geometry for which the relationship between the stress intensity, loads, and crack size is known. This model makes use of three basic equations to obtain the relation between N_t and n:

(1) Fatigue crack growth rate equation.

(2) Acoustic emission-stress intensity factor equation, as expressed in Eq. (7).

(3) The stress intensity factor, load, and crack length relation.

The acoustic emission-fatigue cycle relations are worked out in detail(112,113) for the simple case of a through crack in an infinite plate and for a wedge-opening-loading (WOL) fracture toughness specimen.(115) The theoretical WOL results were compared with experimental observations from trip steel(116) and 7075-T6 aluminum specimens with good correlation. Figure 17 presents the results from two aluminum specimens cycled to 800 pounds, and proofed to 1200 pounds every 3000 cycles. This figure shows the good agreement between the theoretical and experimental results. The amount of acoustic emission observed during the periodic proof increased very rapidly several thousand cycles prior to catastrophic failure, thereby providing early and ample warning of impending failure.

Another indicator of imminent failure is the amount of emission observed while holding at the proof load. If a crack is present with K value close to critical, emission will be observed while holding at constant load. Hence, the presence of emission during a hold provides another warning of impending failure.

The applicability of this technique to pressure vessels has also been demonstrated.(117) Typical results for a welded cylindrical 6061-T6 aluminum vessel will be presented. The vessel had a 4-in. inner diameter, 1/4-in. wall thickness, and welded end caps. It was initially pressurized to 2000 psi, unloaded, and repressurized to 2000 psi. Figure 18 presents the acoustic emission test results of these first two runs.

Very little emission was observed during the repressurization, in agreement with the irreversibility of the emission. The vessel was then cycled to 1300 psi, and proofed to 2000 psi every 3000 cycles while being monitored for emission. The acoustic emission records of the proof tests are presented in Fig. 19, which shows that more emission was observed on each succeeding proof test (except for the one after 3000 cycles). This indicates that a fatigue crack was present and growing during the fatiguing at the working pressure. More emission was observed while holding at the proof pressure for each succeeding proof, which was further evidence of a growing fatigue crack.

The number of counts observed while pressurizing to the proof pressure and the counts while holding at this pressure are plotted as a function of the number of fatigue cycles in Fig. 20. These results show the characteristic marked increase in emission activity prior to failure. Ample and early warning of impending failure was again obtained. Figure 21 contains photographs of the failed vessel, and shows that failure occurred because of fatigue crack propagation in the weld holding one of the end caps on.

These test results indicate that acoustic emission used in conjunction with a periodic overload is capable of providing early warning of impending failure in engineering structures. It can therefore provide a powerful tool for the assessment of structural integrity. It is perhaps worth repeating that, although this has been demonstrated only for the case of fatigue loading, this technique is applicable regardless of the mechanism of the subcritical flaw growth.

4.5 Civil Engineering Structures

Law Engineering Testing Company is applying acoustic emission techniques to a variety of civil engineering problems.

To perform safety inspections on buildings, the building is water loaded. Acoustic emission sensors are placed under the load and on a circle with center on the load line. They have successfully located weld problems in structural steel, deterioration in concrete, and areas of soft wood. In one case, an area damaged by an unreported fire was located.

Standards specify safety inspections of large cranes by complete radiography or ultrasonics on a monthly basis. Acoustic emission transducers attached to critical welds and pin bolts provide adequate warning of a failure mode at much reduced cost.

Law has also monitored the release of prestressing strands in concrete to determine if the prestressing is adequate for critical applications.

Efforts are being made to continuously survey buildings and bridges. It is interesting to note that these applications are being made in the low kHz spectral band, where experts in the field fear to tread.

4.6 Geologic Structures

Application of acoustic techniques in the field have been primarily directed to studies of rockburst phenomena and similar catastrophic failure processes in underground excavations. Extensive studies have been conducted by Russian investigators to relate seismo-acoustical or acoustic emission activity with rockburst in mines.(56) The results of these studies have prompted the use of acoustic techniques on a routine basis for forecasting sudden outbursts of coal and gas in mines.

Cadman and Goodman, using acoustical monitoring of real landslides, have revealed the existence of subaudible noise activity prior to failure, allowing a prediction of the depth of seat sliding.(118) Similar techniques have been used in Swedish hydro-electric works of copper mines.(119, 62) Hardy proposed the use of acoustic techniques to assess the stability of storage areas and to develop criteria for determining optimum pressures for underground storage of natural gas.(120, 121)

Scholz,(70) Mogi,(72) and Armstrong(74) have noted the various similarities between micro-seismic activity, rock fracturing, and earthquake phemonena with hopes of clarifying some of the criteria in earthquake prediction.

Knill et al. conclude that acoustic emission studies are widely applicable to rock mechanics and provide an excellent review.(63) Application of acoustic emission techniques to supplement or support other experimental techniques may well contribute to an understanding of many rock engineering problems and provide a useful tool for studying material behavior.

5. SUMMARY

Acoustic emission techniques have wide applicability to experimental studies in materials research and to evaluation analysis of structural integrity. The experimental technique is very sensitive to dynamic transient processes in materials, such as mechanistic processes operative during plastic deformation and crack growth, crack initiation and propagation, fracture processes, and martensitic transformations.

We have presented a brief historical sketch of emission studies. A discussion of the experimental critieria was given, which included a discussion of the essential principles of transducer design and electronic and mechanical considerations, and the data acquisition, processing, and display systems. Also, frequency response and detection fidelity were analyzed and a discussion of the limitations of acoustic emission technique was presented.

Emission behavior of metals during straining has been reviewed for unflawed and flawed materials. Subcritical flaw growth during pop-in, stress corrosion cracking, fatigue, and hydrogen embrittlement results in the release of elastic strain energy, which gives rise to acoustic emissions and can be readily detected by acoustic emission techniques. Quantitative information regarding the imminence of failure can be obtained from emission data.

Criteria for the deformation and failure of composite materials are complex. The discussion of these processes in dispersion, particle, and fiber composites concluded that emission analysis was well suited for establishing the mechanisms governing fracture modes and assessing the structural integrity. Results of tensile tests and fatigue studies were presented.

Because of the transient nature of the mechanistic processes involved in the deformation and fracturing of rocks, acoustic emission analysis is particularly appropriate. Each deformation and fracture process from the movement of cracks on initial stress application to the final rupture mechanisms is ideally suited to emission analysis. Each involves a transient process which is a known generator of emission activity. Thus, emission techniques have a wide application in laboratory and field experiments in the field of rock mechanics.

Results of laboratory studies indicate that acoustic emissions generated by plastic deformation and crack initiation and propagation are easily detected. Therefore, emission analysis has been applied in a variety of ways to evaluation of structural integrity. The results of studies discussed previously show that emission techniques can readily assess the integrity of joining processes. Early indications of flaw growth are signaled by emission activity in pressure vessels. Triangulation techniques are used to locate critical areas. Emission monitoring during periodic overload of structures in service provides a direct means of assessing whether or not the service environment has deteriorated the structure in any way. Emission techniques have been applied with success to large complex structures such as bridges, airframes, and the earth itself.

Future application of acoustic emission techniques to problems of structural integrity is unlimited. Flaw detection sensitivity is greater than any other known technique of nondestructive testing. Acoustic emission provides the opportunity to detect subcritical flaw growth in real time as no other method can. Emission is easily detectable in noisy environments such as exist in production facilities. Quality control inspections of critical or warranty parts is possible with equipment commercially available. Such tests require only fixturing to apply appropriate proof loads and should be much more reliable than present inspection techniques.

The method with more complex and costly data reduction equipment has proved successful in locating flaws in pressure vessels during hydro-test. Detection problems still exist when cavitation and boiling occur, as found in operating nuclear power plants, or when friction noise is present as in riveted or bolted frame structures. Even in some of these high-noise situations, acoustic emission can be used to monitor known critical areas. The solution to the noise problem for locating developing flaws in unknown locations requires imaginative application of available signal processing techniques.

Acoustic emission is a very useful tool for material evaluation and structural integrity studies. Utilization of this technique is in its early stages. Experimental techniques and instrumentation are now reasonably developed to the level where they can be immediately applied. Tremendous potential exists in basic studies from the atomic level to gross phenomena. Applications for acoustic emission analysis are innumerable. The diversity of the technique is readily shown by noting that it is applied in studies of dislocation dynamics in materials, and, at the other extreme, is applied to earthquake studies and integrity evaluation of large missile casings.

6. FUTURE DEVELOPMENTS

The imaginations of engineers and scientists will determine the direction of future developments and applications of acoustic emission techniques. In the immediate future, several areas appear fruitful. Transducer design is one. New generations of piezo-electric crystals with greater sensitivity and lower noise would be advantageous. Improvement of existing crystals by plating with a semiconductor for amplification (electro-acoustical amplification) is in early development stages.(122) Development of small crystals would extend the state-of-the-art. Transducers for use at high temperatures would greatly extend the applicability of emission analysis to high-temperature processes.

Use of acoustic emission techniques in basic research studies of material phenomena has been rather limited. It appears that the emission activity associated with dislocation dynamics could be studied in a fundamental manner with acoustic emission techniques.(123) Studies of twinning, discontinuous-slip, breakaway of dislocations from obstacles, creep processes, martensitic transformations, and magnetic domain rearrangement are a few other possibilities.

In applied areas, material processes such as casting, rolling and forging hold promise for analysis by acoustic emission techniques. Quality assurance programs involving proof testing by periodic overload before, during, and after service is perhaps the most promising area of application in the immediate future. An "on-line" test for flaws and cracks in production is another immediate application.

ACKNOWLEDGMENTS

We wish to thank our many colleages at Lawrence Radiation Laboratory for their encouragement and helpful discussions throughout our acoustic emission program. We especially wish to thank A. Brown, B. Kuhn, H. Appleton, and D. Green for their technical assistance in advancing our experimental techniques. Also, we wish to express our gratitude to T. Nelson of the Technical Information Department for his valuable editorial comments and suggestions.

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123. B. H. Schofield, *Acoustic Emission Under Applied Stress*, Lessells and Associates, Cambridge, Mass., Rept. ASD-TDR-53-509 Part I (1963) and ASD-TDR-63-509 Part II (1964).

FIGURE CAPTIONS

Fig. 1. Acoustic emission and stress vs. strain for a 7075-T6 aluminum tensile specimen. Dashed curve is a fit of Gilman's theoretical expression for mobile dislocation density vs. plastic strain.(32)

Fig. 2. Fourier integral transform plots for model event. (a) Phase. (b) Amplitude.

Fig. 3. Summation acoustic emission as a function of load for four SEN fracture toughness specimens of 7075-T6 aluminum with varying crack lengths.(32)

Fig. 4. Summation acoustic emission as a function of stress intensity factor for four single-edge-notch fracture specimens with varying crack lengths. A best-fit fourth power curve was drawn through the data points.(32)

Fig. 5. Summation counts vs. tensile load for multiflawed specimens.(32)

Fig. 6. Summation counts vs. stress intensity factor for multiflawed specimens.(32)

Fig. 7. Acoustic emission and notch opening displacement as functions of load for a single-edge-notched specimen of 7075-T6 aluminum.(26)

Fig. 8. Relationship between crack growth rate and stress-wave emission for two conditions of D6Ac steel.(41) [Reproduced from: C. E. Hartbower, W. W. Gerberich, and P. P. Crimmins, "Monitoring Subcritical Crack Growth by Detection of Elastic Stress Waves," Weld J. (New York) 47 (1), 55 (1968)].

Fig. 9. Stress intensity factor and acoustic emission as a function of time for a crack propagating in a uranium-0.3% titanium alloy immersed in a 3% salt-water solution.(33)

Fig. 10. Number of breaks as a function of applied load.(49) [Reproduced from: C. Zweben, "Tensile Failure of Fiber Composites," AIAA J. 6 (12), 2329 (1968)].

Fig. 11. Summation of acoustic emissions as a function of applied load on a filament-wound NOL ring.

Fig. 12. Stress and acoustic emission as a function of strain for whisker-reinforced $Al-Al_3Ni$ composite showing emission curves predicted from model.

Fig. 13. Percentage of broken whiskers as a function of strain for $Al-Al_3Ni$ composite.

Fig. 14. Summation of acoustic emission as a function of applied load on an NOL ring. Ring was cycled to 4000 pounds and intermittently proofed to 6000 pounds.

Fig. 15. Bieniawski's scheme for considering rock fracture in compression.(52)

Fig. 16. Acoustic emission rate as a function of strain on Sturdevant Quartzite, confining pressure 3.5 kbar. After initial failure (first drop in acoustic emission activity), further deformation proceeds by stick-slip.

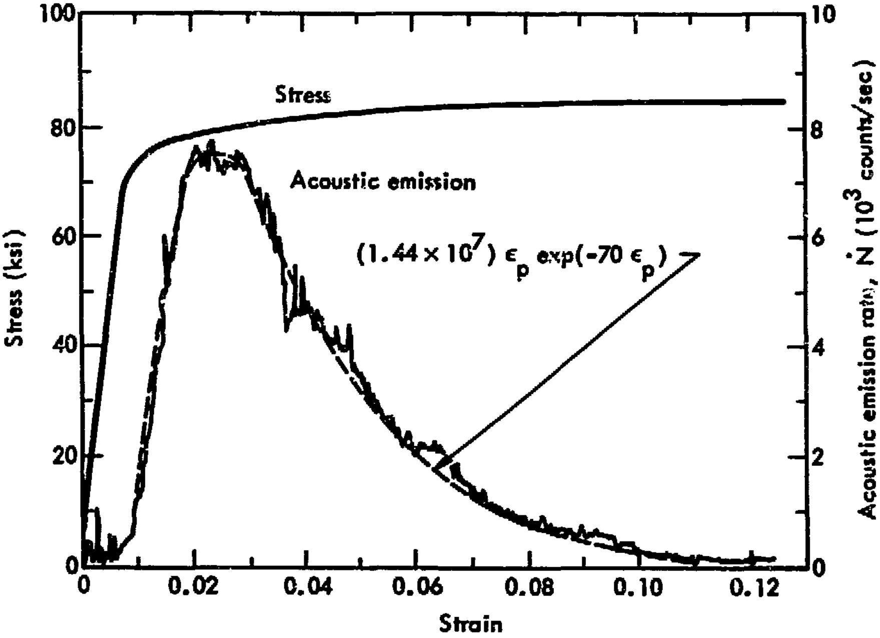
Fig. 17. Theoretical and experimental results of periodic proof tests with acoustic emission from 7075-T6 WOL fracture toughness specimens.(113)

Fig. 18. Summation of acoustic emission as a function of pressure for initial pressurization and first re-pressurization of pressure vessel.

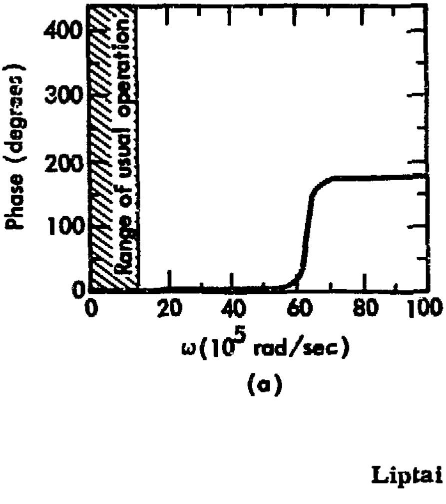
Fig. 19. Summation of acoustic emission as a function of pressure for intermittently proofed cyclically loaded pressure vessel. Numbers by curves are the number of fatigue cycles in thousands of cycles.

Fig. 20. Total acoustic emission observed during proof to 2000 psi as a function of fatigue cycles to 1300 psi for intermittently proofed cyclically loaded pressure vessel.

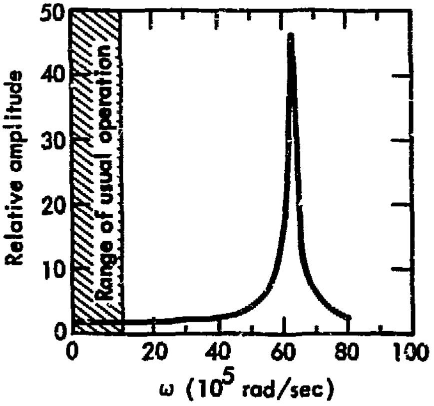
Fig. 21. (a) Failed pressure vessel. (b) Fracture surface and fatigue crack growth markings.


Stress
Acoustic emission
$(1.44 \times 10^7)\, \epsilon_p \exp(-70\, \epsilon_p)$
Stress (ksi)
0
20
40
60
80
100
Strain
0
0.02
0.04
0.06
0.08
0.10
0.12
Acoustic emission rate, $\dot{N}$ (10^3 counts/sec)
0
2
4
6
8
10

Liptai - Fig. 1

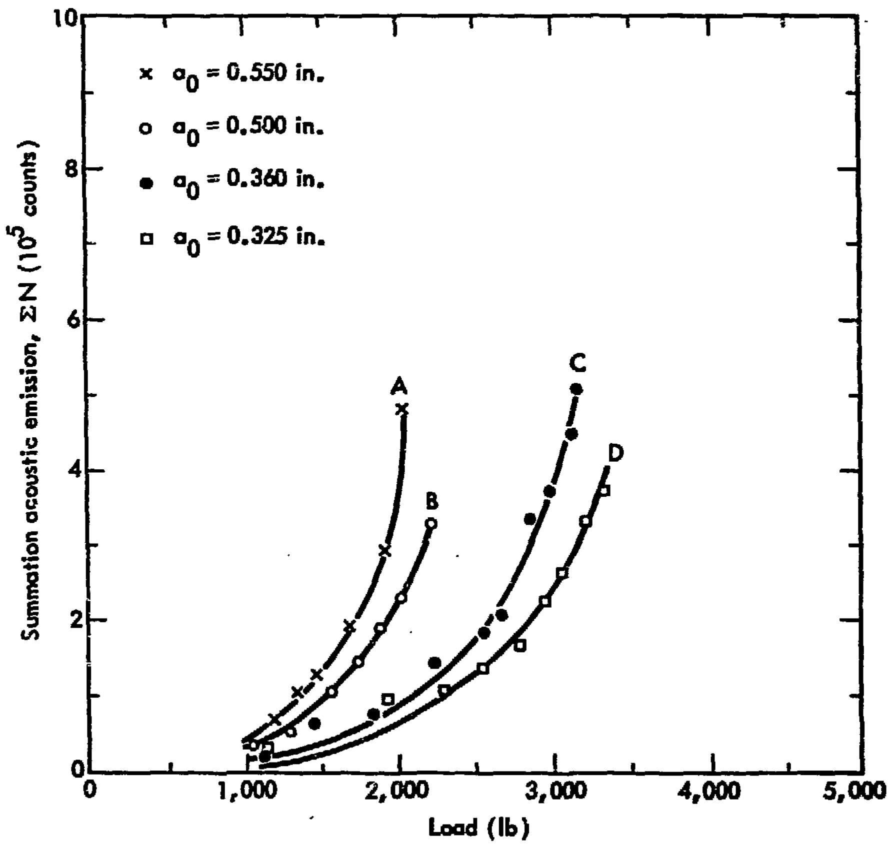


Liptai - Fig. 2a

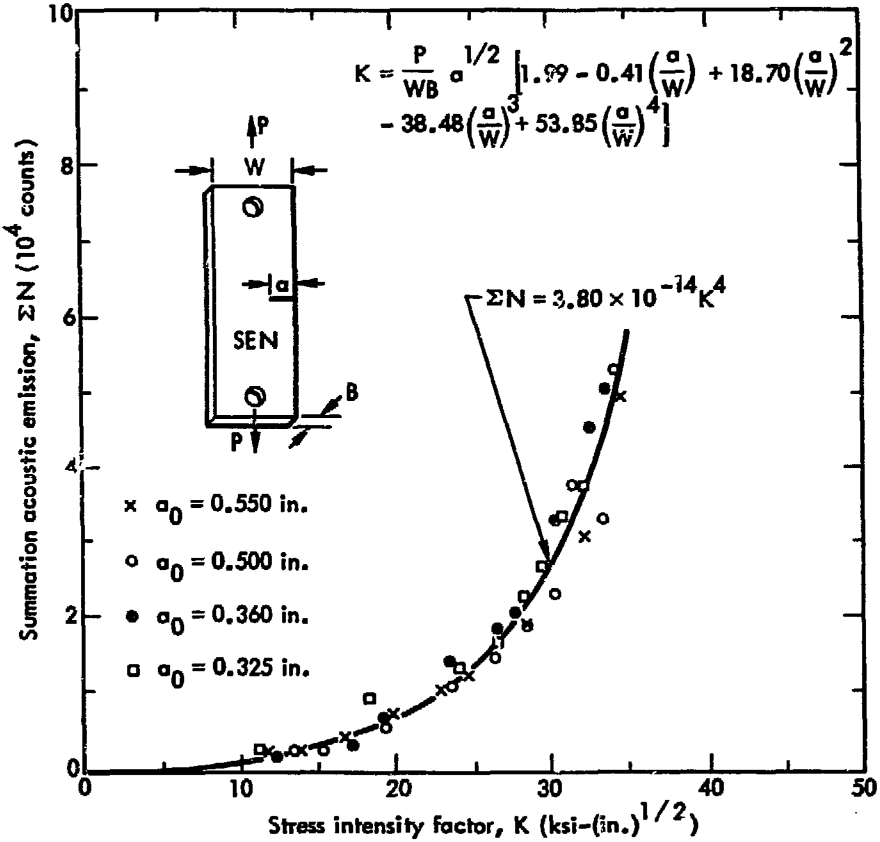


(b)

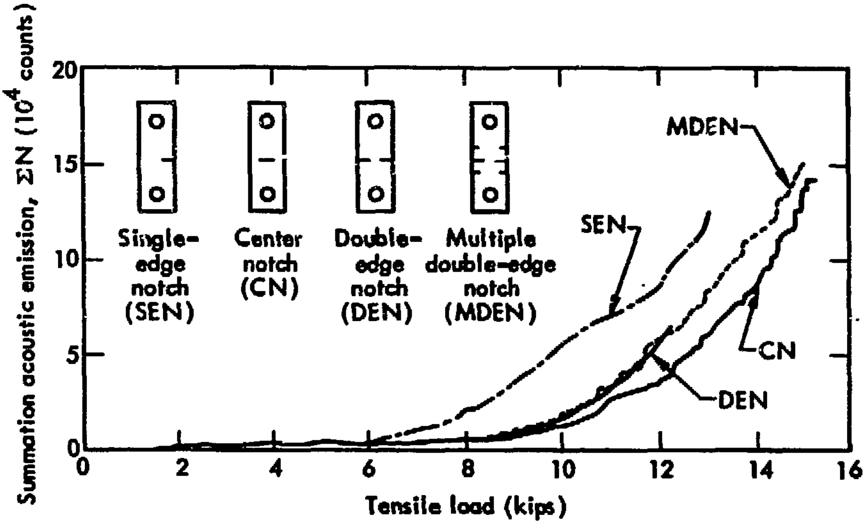
Liptai - Fig. 2b


× a_0 = 0.550 in.
○ a_0 = 0.500 in.
● a_0 = 0.360 in.
□ a_0 = 0.325 in.
A
B
C
D
Summation acoustic emission, ΣN (10^5 counts)
0
2
4
6
8
10
0
1,000
2,000
3,000
4,000
5,000
Load (lb)

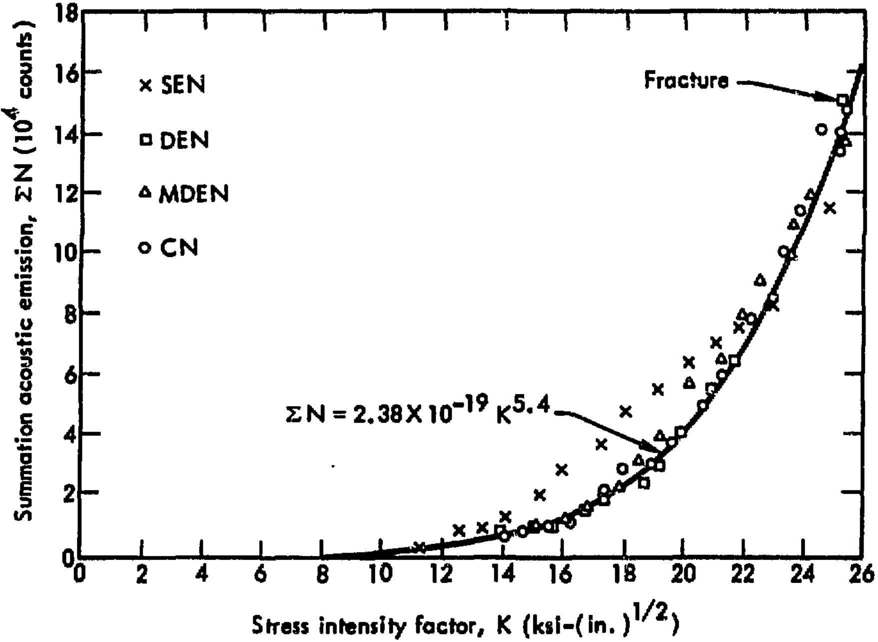
Liptai - Fig. 3

$K = \frac{P}{WB} a^{1/2} \left[1.99 - 0.41\left(\frac{a}{W}\right) + 18.70\left(\frac{a}{W}\right)^2 - 38.48\left(\frac{a}{W}\right)^3 + 53.85\left(\frac{a}{W}\right)^4\right]$
P
W
a
SEN
B
P
$\Sigma N = 3.80 \times 10^{-14} K^4$
× a_0 = 0.550 in.
○ a_0 = 0.500 in.
● a_0 = 0.360 in.
□ a_0 = 0.325 in.
Summation acoustic emission, ΣN (10^4 counts)
0
2
4
6
8
10
0
10
20
30
40
50
Stress intensity factor, K (ksi-(in.)$^{1/2}$)

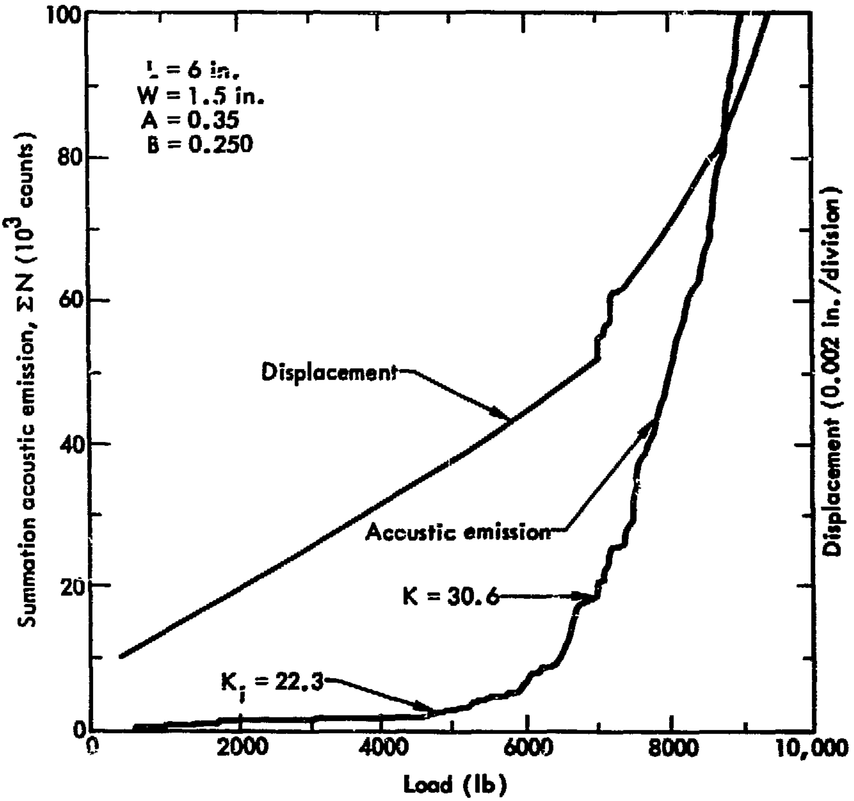
Liptai - Fig. 4


Summation acoustic emission, ΣN (10^4 counts)
20
15
10
5
0
0
2
4
6
8
10
12
14
16
Tensile load (kips)
Single-edge notch (SEN)
Center notch (CN)
Double-edge notch (DEN)
Multiple double-edge notch (MDEN)
MDEN
SEN
CN
DEN

Liptai - Fig. 5

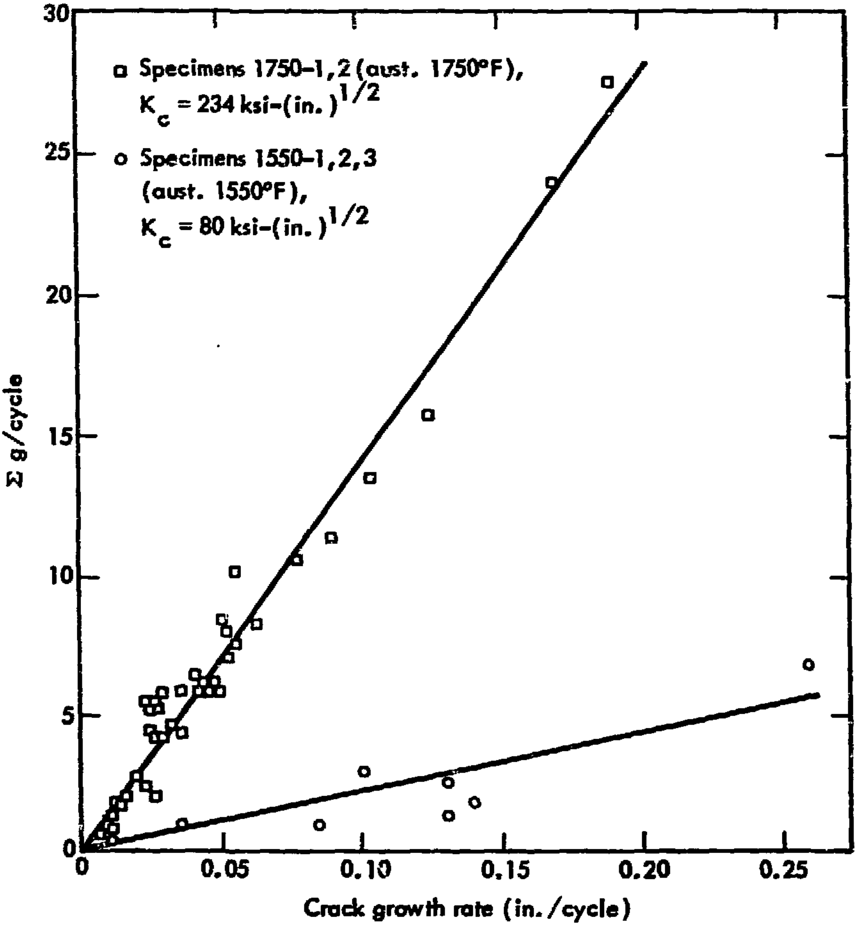

Summation acoustic emission, ΣN (10^4 counts)
0
2
4
6
8
10
12
14
16
18
× SEN
□ DEN
△ MDEN
○ CN
Fracture
$\Sigma N = 2.38 \times 10^{-19} K^{5.4}$
0
2
4
6
8
10
12
14
16
18
20
22
24
26
Stress intensity factor, K (ksi-(in.)$^{1/2}$)

Liptai - Fig. 6

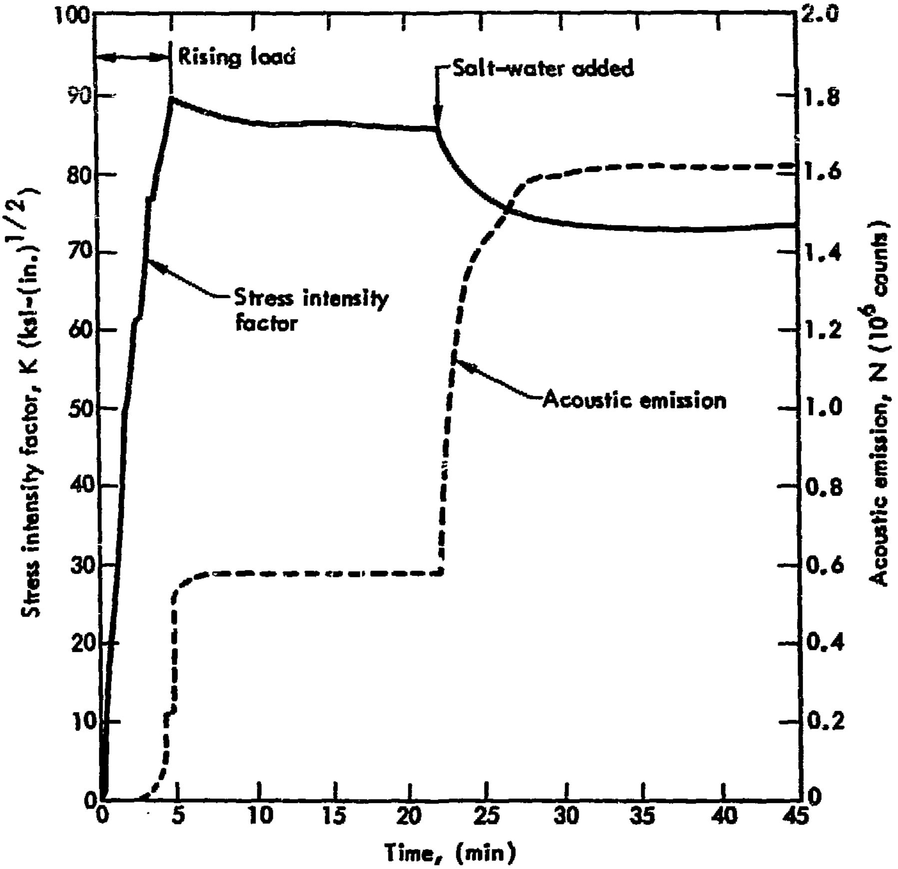


L = 6 in.
W = 1.5 in.
A = 0.35
B = 0.250
Displacement
Acoustic emission
K = 30.6
K_i = 22.3
Summation acoustic emission, ΣN (10^3 counts)
Displacement (0.002 in./division)
Load (lb)
0
20
40
60
80
100
0
2000
4000
6000
8000
10,000

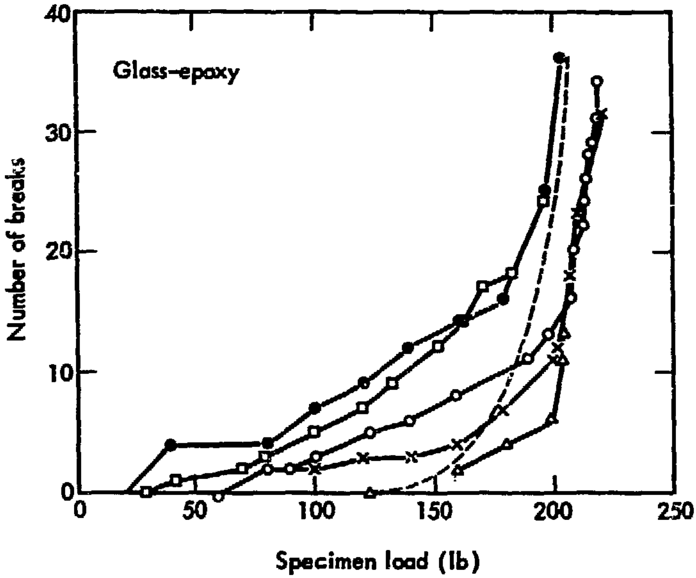
Liptai - Fig. 7


□ Specimens 1750-1,2 (aust. 1750°F),
K_c = 234 ksi-(in.)$^{1/2}$
○ Specimens 1550-1,2,3
(aust. 1550°F),
K_c = 80 ksi-(in.)$^{1/2}$
Σ g/cycle
30
25
20
15
10
5
0
0
0.05
0.10
0.15
0.20
0.25
Crack growth rate (in./cycle)

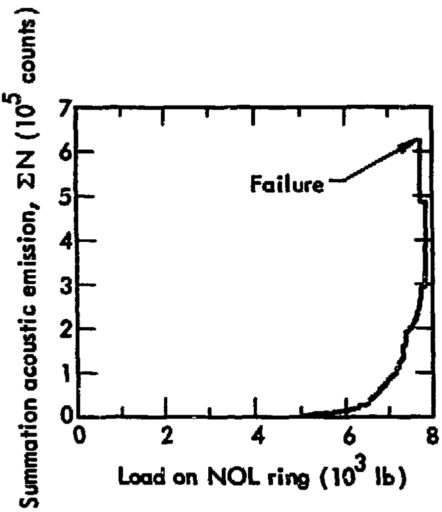
Liptai - Fig. 8


100
90
80
70
60
50
40
30
20
10
0
Stress intensity factor, K (ksi-(in.)$^{1/2}$)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
Acoustic emission, N (10^6 counts)
0
5
10
15
20
25
30
35
40
45
Time, (min)
Rising load
Salt-water added
Stress intensity factor
Acoustic emission

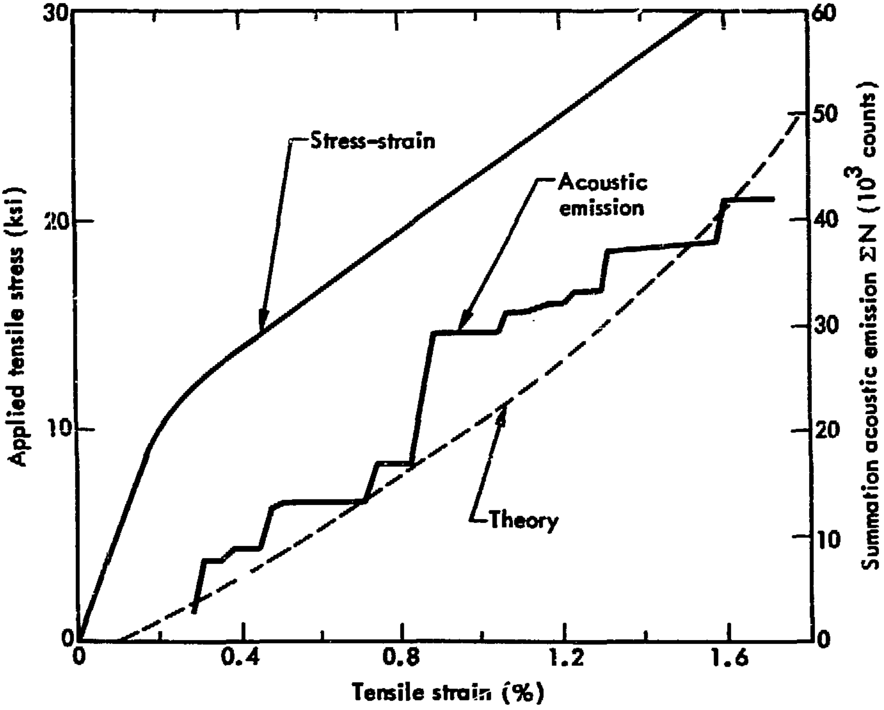
Liptai - Fig. 9



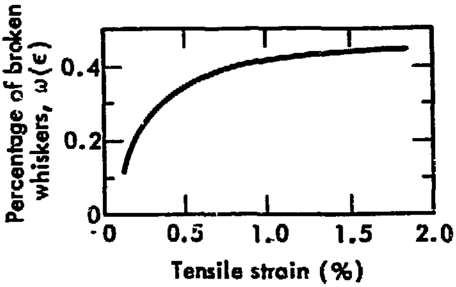
Liptai - Fig. 10



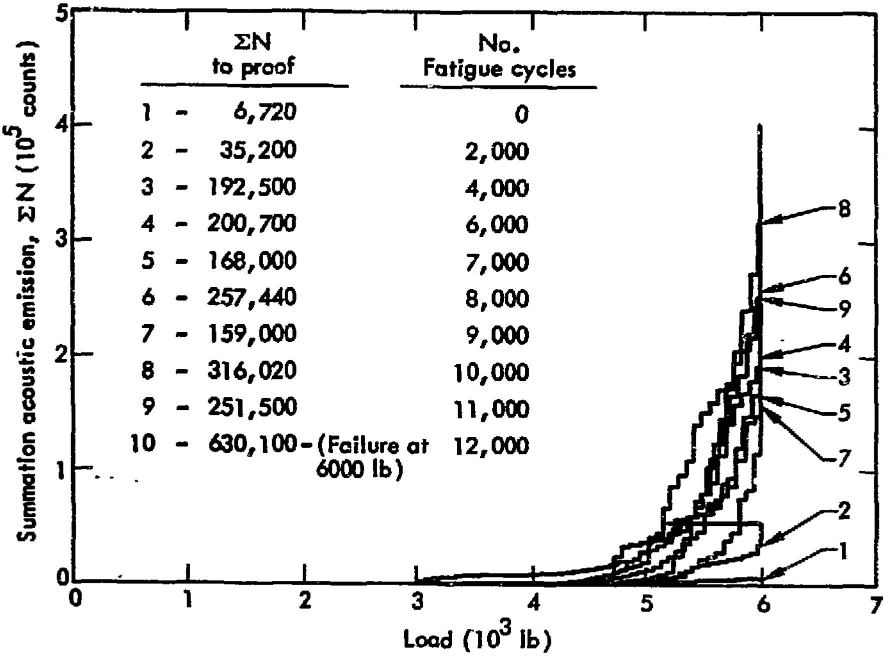
Liptai - Fig. 11



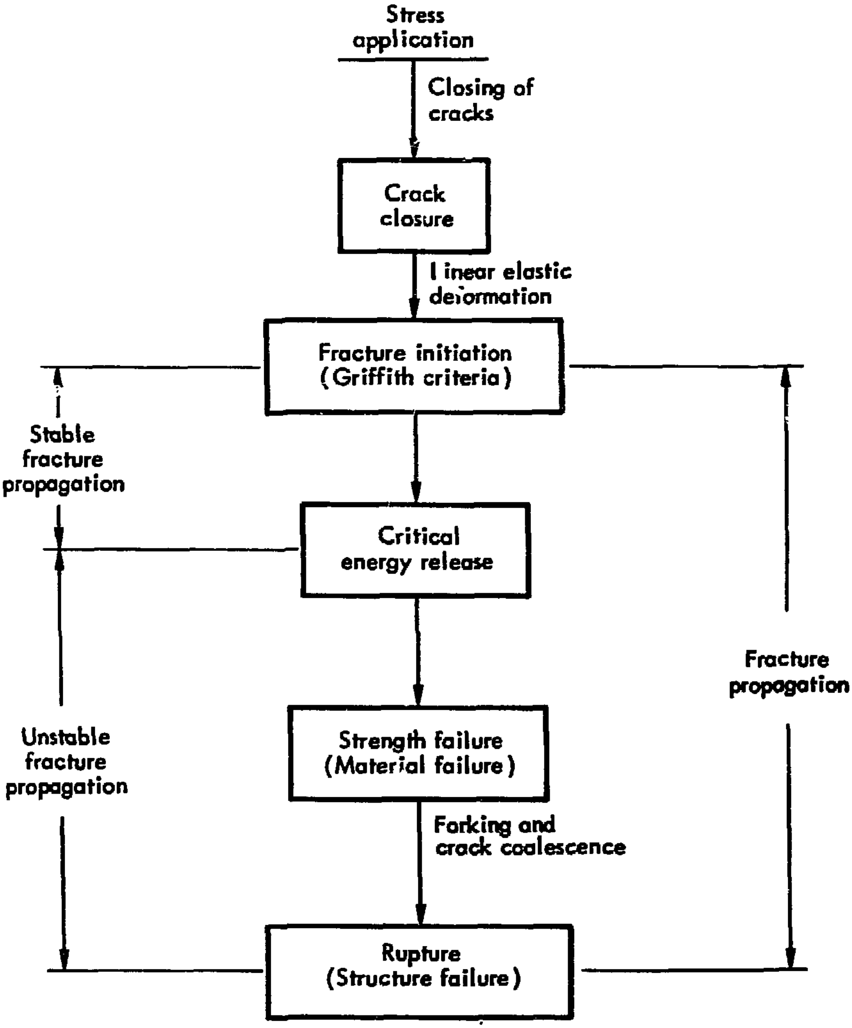
Liptai - Fig. 12



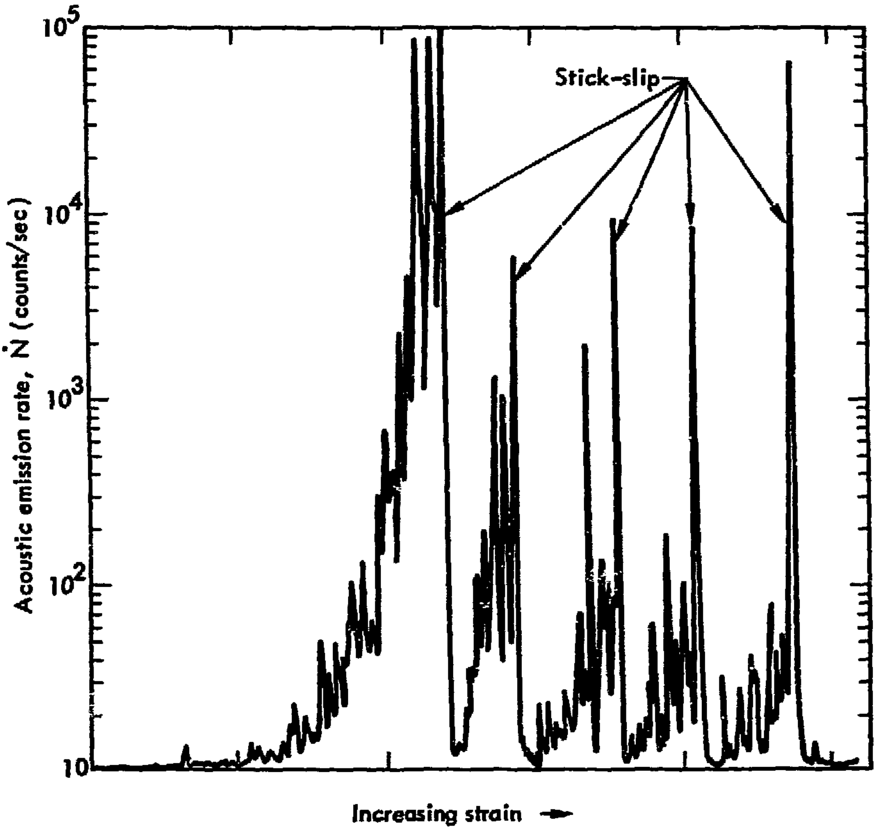
Liptai - Fig. 13



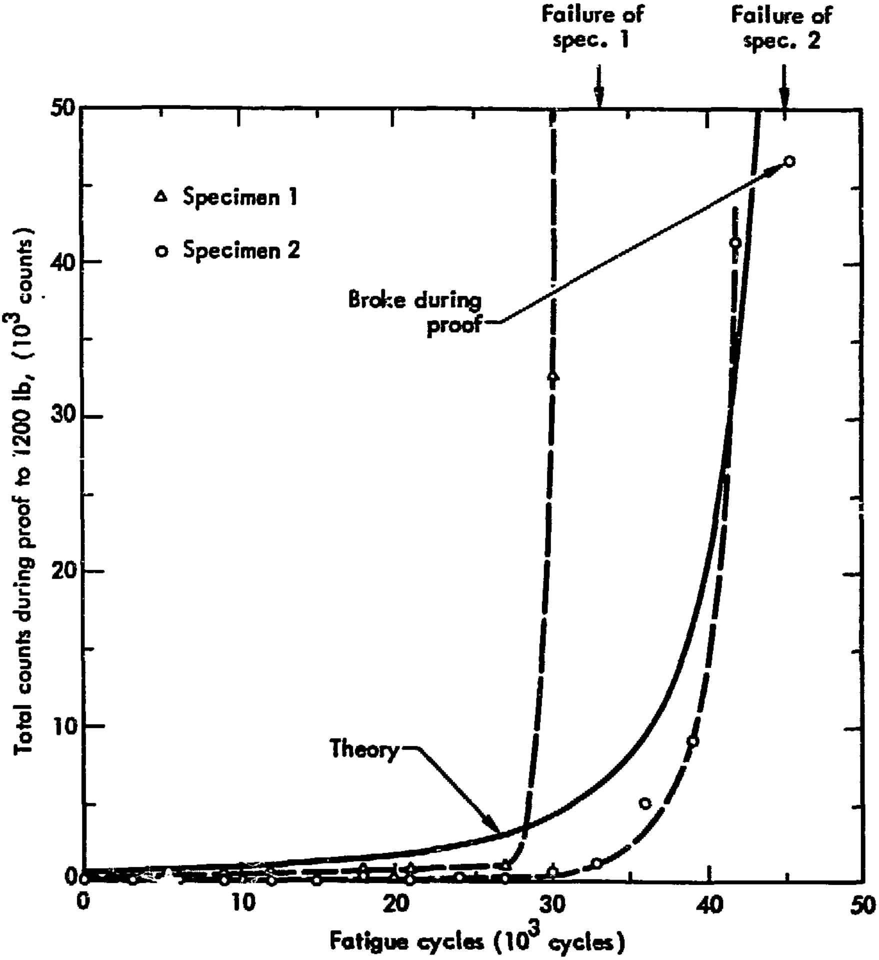
Liptai - Fig. 14



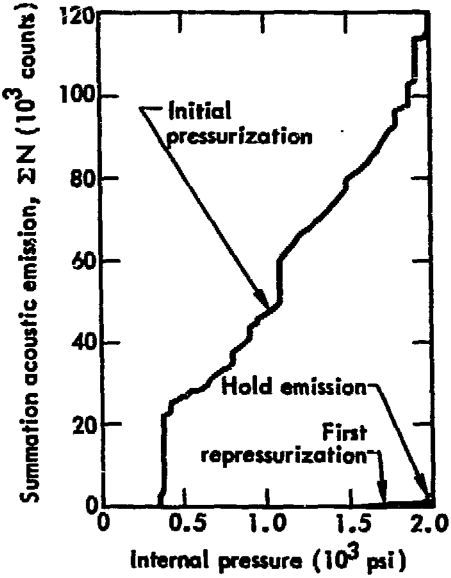
Liptai - Fig. 15



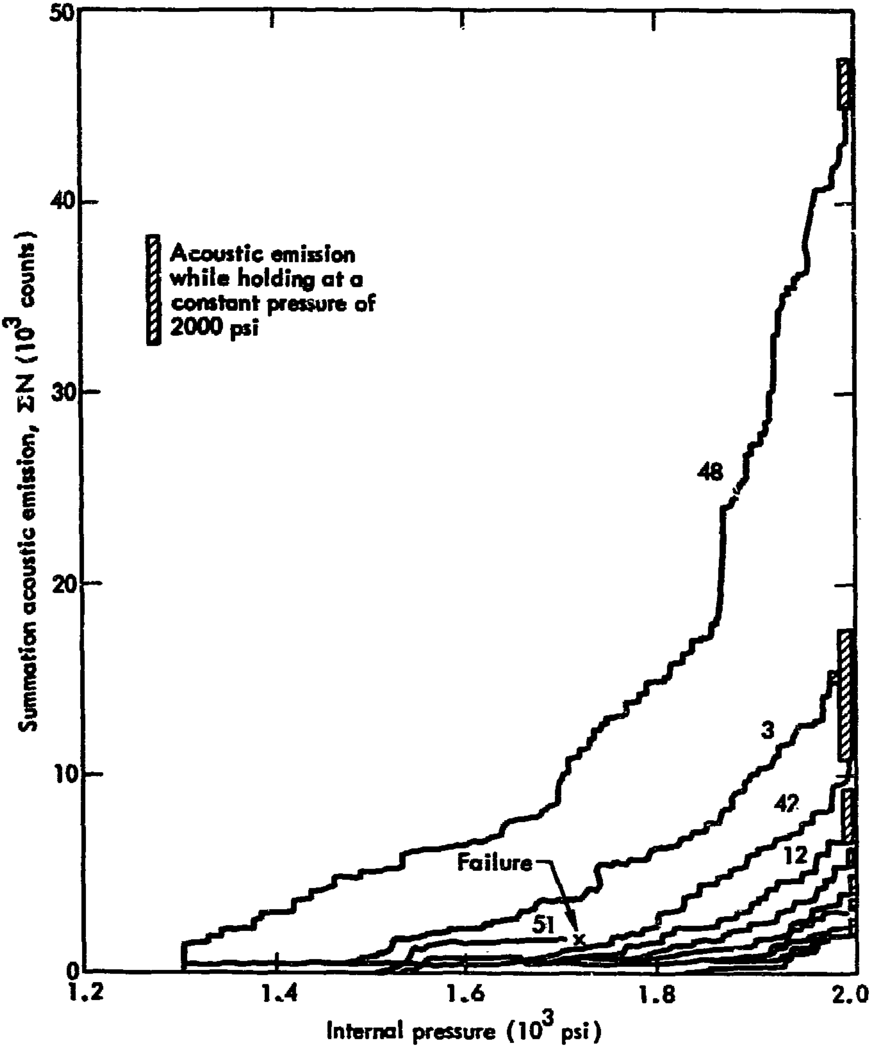
Liptai - Fig. 16



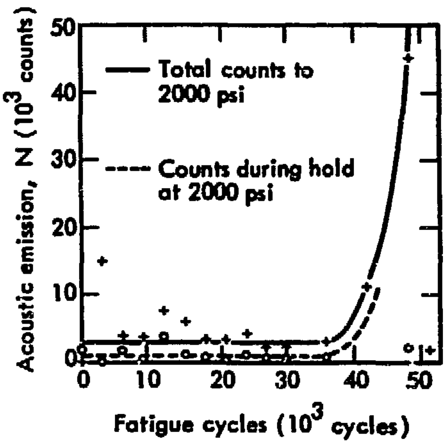
Liptai - Fig. 17



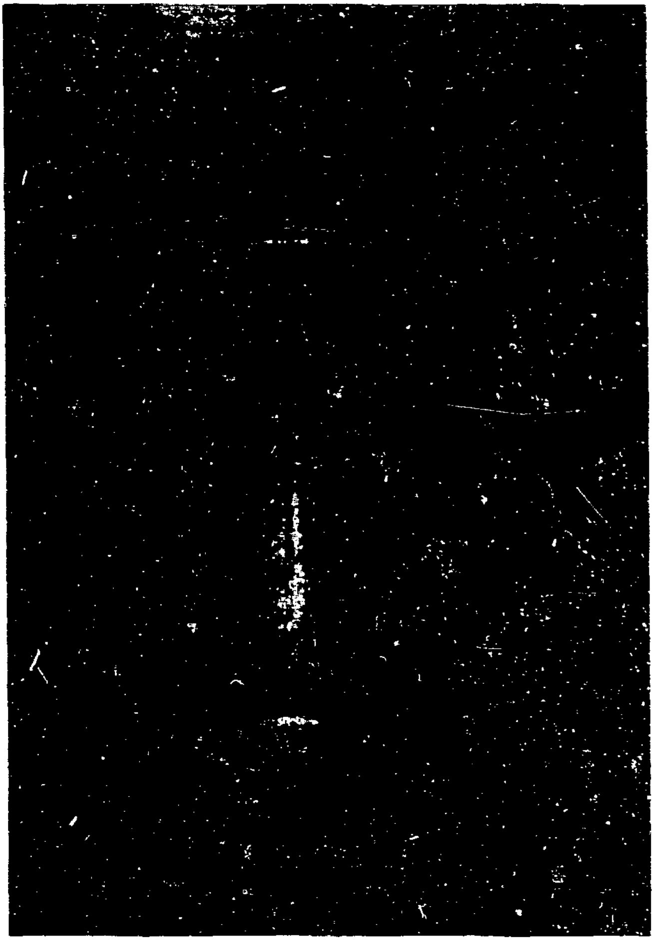
Liptai - Fig. 18



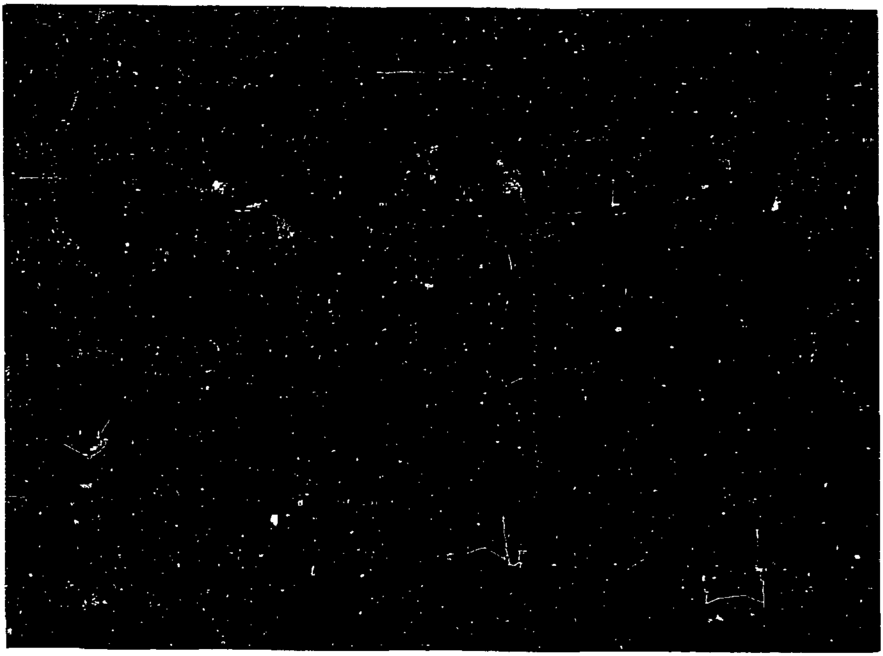
Liptai - Fig. 19



Liptai - Fig. 20



(a)



(b)

Liptai - Fig. 21(b)