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ACOUSTIC EMISSION FROM COMPOSITE MATERIALS

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ACOUSTIC EMISSION OF COMPOSITE MATERIALS

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1. Introduction

Interest in composite materials has recently increased rapidly because of the growing research on materials with high resistance and low specific weight. As far as their use is concerned, however, there remain certain difficult problems, such as the relative difficulty in the study of the characteristics of deformation and fracture, and in non-destructive evaluation of the material's integrity. /1*

Acoustic emission (A. E.) is a fascinating technique, relatively new and extremely promising for the solution of such problems. This report attempts to show the applicability of this technique, especially to fiber reinforced plastic materials, and to review briefly the fundamental concepts underlying A. E. and the results obtained to date in this field.

Acoustic emissions are impulses of pressure generated by the deformation energy liberated within a material during the development of dynamic processes. Thus if application of a load to a material causes damage, such as propagation of cracks or development of internal defects, energy is liberated and propagated in the form of vibrations to the material's surface.

A. E. techniques consist of "listening" to these vibrations, which constitute a potentially very rich source of information on the internal processes of deformation. A. E. can indicate events characterized by very small amounts of energy, provided that the experimental conditions

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*Numbers in the margin indicate pagination in the foreign text.

are satisfactory. It has been applied to the study of various processes, ranging from dislocation movement [1] in metals to extension of cracks in large pressure vessels [2].

The data furnished by these techniques can be used either for studying the properties and behavior of the materials under examination, or to single out possible damages by means of non-destructive control procedures.

In fact, A.E. detects only damage that is produced or continued /2 during auscultation. This means that the specimen or structure under examination must be loaded mechanically. The necessity of loading the material seems contrary to the concept of non-destructive testing, but it allows detection of propagating defects rather than other defects, also large, but non-critical since they do not tend to propagate themselves. A.E. techniques, however, can be considered completely non-destructive, for only when there are defects present or the specimen or structure becomes overcharged, are acoustic signals detected.

A fundamental property of A.E., which is exploited in many applications, is the so-called "Keiser effect," named after the man who pioneered the study of acoustic emissions from materials with the aid of electronic equipment [3]. This effect consists of the irreversability of emissions: acoustic emissions are not generated during the reloading of a material so long as the stress level does not exceed the maximum value previously attained. This property has been proven valid for metallic materials and exploited in non-destructive testing, because the maximum load attained during the service of any component of a structure thus can be re-attained.

For composite materials there still remains some doubt among certain experimenters [4, 5] concerning the validity of this property, but others [6, 7, 8] believe the Keiser effect to be proven valid for composite materials as well.

2. Acoustic Emission Techniques

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A source of A.E. impulses can be imagined as a point, like a microscopic concentration of deformation energy which, through sudden irreversible phenomena, transmits a portion of its stored energy in the form of a wave of spheric pressure. This wave's energy is distributed homogeneously under a very broad frequency band, from 0 to 50 MHz, according to estimates made with reference to metallic materials [9].

Of this spectrum, only the frequencies between 20 kHz and 1.5 MHz are of practical use.

At higher frequencies the A.E. is too weak and the attenuation (due to the mechanisms of energy loss within the material) too great, especially in composite materials because of the deviations and dispersions due to their dishomogeneity, and the effects of elastic damping in polymer materials. At lower frequencies the extraneous noises (mechanical, sonorous, etc.) are generally too great. The sensitivity of the measurements is at its maximum when they are made at the lowest frequencies possible, taking into account interference noises.

The pressure waves can travel within the material in two different forms: longitudinal waves and transversal waves. At the material's surface, however, the waves are transmitted in the form of Rayleigh waves. Each mode of propagation has its own characteristic propagation velocity and attenuation trend, and both of these properties are functions of the frequency. Other waves are generated by the reflections on the internal surfaces of the materials, and by the excitation of resonances in the specimen or structure.

In some materials the acoustic signals may be so strong as to be audible, as in the classic case of tin "squealing" or when beams of wood are broken, but in general the total energy of a sonic impulse is on the order of 1.000 eV, about 1.6×10^{-16} joule [10]. Naturally /4
such weak signals require a transducer and adequate electronic equipment

in order to be picked up.

Since acoustic emissions are really pressure waves, they can be detected by means of piezoelectric or accelerometric transducers. These transform the mechanical impulse coming from the material into an electric signal, due to a sudden rise and slower fall in stress generated on two opposite faces of the crystal within the transducer [11].

If a resonant transducer is used, the electrical signal produced does not correspond exactly to the original pressure wave. When it is submitted to an impulse of pressure, the transducer oscillates with reduced sinusoid oscillations of frequency close to that of the resonance of the quartz crystal, and the voltage V at the transducer instant t is given by the equation:

$$V_t = V_p e^{-kt} \sin \omega t \qquad (1)$$

where V is the initial stress, k is a damping constant of about 10% and ω is the pulsation equal to $2 \pi \nu$ (ν = frequency). Figure 1 shows schematically the signal given by the transducer.

The weakness of the signals coming from the transducer, on the order of a few microvolts, requires a stage of electronic amplification, and the need to eliminate spurious noises requires use of an electronic filter.

An A.E. detection system is composed (besides the transducer, amplifier, and filter) of a threshold comparator, whose threshold level is generally fixed at 1 V, and an electronic counter.

The signals exceeding the threshold level can be processed in various ways. The simplest way is as follows: make a count of all oscillations exceeding the threshold ("ring-down" count). In /5
Figure 1 it can be seen that when the threshold level decreases, the number of count units increases. The number of peaks is given by:

$$N = \nu t' = \omega t'/2\pi \qquad (2)$$

where t is the instant at which the voltage coming from the transducer exceeds the threshold value for the last time. Since the last peak is at a distance of an integer number of wavelengths from the origin plus 1/4 of the wavelength, equation (1) becomes:

$$V_{t'} = V_o \; e^{-kt'} \qquad (3)$$

In this case then, the number of counts registered by the instrument for a single event is:

$$N = \omega/K2\pi \quad \ln \quad V_o/V_{t'} \qquad (4)$$

One can also obtain the envelope of the oscillation that was reduced due to the A.E. impulse in such a way that a single count unit corresponds to each event ("event counting").

In both "ring-down" and "event counting" the count rate can be obtained by deriving the total number of signals with respect to time.

By means of a digital/analog converter, an electric signal can be sent, proportional to the preselected A.E. parameter (total number of oscillations or events or their count rate) to an axis of an x-y graphic recorder, while the other axis is sent a signal proportional to a load parameter, or even simply a time parameter.

Generally the cumulative curves of acoustic emission can be composed of a large number of small impulses (containing emission), or a relatively small number of large discharges of impulses (discharge emission). These two procedures are shown in Figures 2 and 3.

Figure 4 shows the block scheme of a typical A,E, detection system. As this figure also indicates, it should be taken into /6 account that more sophisticated techniques of data processing can be used: e.g., frequency analysis, amplitude distribution, and energy measurements [14-18]. If instead of the counter a frequency analyzer is used, the individual impulse can be analyzed in such a way as to obtain its spectrum; thus one can try to identify the particular type of event that generated the impulse by means of its fundamental frequency. The impulses can also be analyzed by distributing them according to their amplitudes.

These are counted in different channels characterized by different threshold levels. By operating in this way, it is possible to attain another measurement of the energy involved in the phenomenon by means of the expression $E=\sum n_i A_i^2$

used by some experimenters [12-13] (ni = number of signal counts between A and A_{i+1} where A is the threshold level of the i-th channel).

If a system with more channels is used, the defect can be localized. By using three transducers on a surface and measuring the differences in arrival time of the signals at each transducer, one can return, by means of triangulation techniques, to the position of the defect that is an A.E. source.

It is necessary, however, to realize that the transducer's outlet signal cannot be directly correlated with the original pressure impulse, because of the indicated phenomena of reflection and interference in the material, the excitation of resonance in the specimen and in the transducer itself, the spatial attenuations and the sensitivity level of the equipment used.

3. Application to the Study of Materials /7

In the laboratory A.E. techniques have been used on a very diverse range of materials, such as aluminum monocrystals and beams of wood, and they have had very diverse applications, such as the study of earthquake models and non-destructive controls of large pressure vessels for nuclear reactors.

Most of this work has been conducted in the field of plastic deformation and crack propagation in metals. By way of example we offer the diagram in Figure 5 where the trend of A.E. count speed is shown as a function of the deformation of a 7075-T6 aluminum specimen, superimposed on the a - curve for the same specimen.

The peak corresponding to deformations near the point of weakening is a typical result for metals. The figure also shows the excellent adaptation of Gilman's equation for the density of mobile dislocations, as a function of the deformation, to the A.E. trend; this suggests the existence of a strict relation between A.E. and dislocation movement, responsible for the plastic deformation of metals [2].

Figure 6 shows the results of tests done on the same type of material, but with specimens of various shapes containing fatigue cracks.

The results show that the factor of stress intensity $K = \sigma\sqrt{\pi a}$ completely controls the fracture process. Specimens with different crack lengths (a) and loaded differently, but with equal factors of stress intensity K, behave in the same way in comparisons of the fracture, according to the principles of the mechanics of elastic linear fracture.

A.E. also depends on K, for which reason it can be used to detect critical cracks in order to furnish information on engineering structures [2].

Composite materials seem ideal for the application of the A.E. technique in as much as various mechanisms of fragile failure can /8 be developed in them, with sudden release of energy, which may culminate in immediate catastrophic failure or in compliance due to the accumulation and propagation of microbursts.

The A.E. of composite materials may come from the deformation and bursting of the matrix, from the failure of the matrix-reinforcement phase interface, and from the deformation and failure of the reinforcement phase. Bearing in mind these fundamental mechanisms of A.E. production, we see the acoustic behavior of the three categories into which composite materials in general may be divided: a) dispersion reinforced, b) particle reinforced, and c) fiber reinforced.

In composites reinforced with a dispersion of very small particles (0 = 0.01 + 0.1 M) where the matrix is the constituent that bears the load, the A.E. is continuous and low-level, of the type characteristic of metals.

In composites reinforced with particles of diameter greater than 1 M and with a concentration above 25%, two cases can occur: if the reinforcement particles do not become deformed before the fracture occurs, the same response as with the dispersion-reinforced composites occurs, with regard to A.E. If the particles become plastically deformed, a double emission activity is obtained, one relative to the matrix and the other to the particles.

The fundamental microstructural characteristic of fiber reinforced composites is the long prevailing dimension of the reinforcement. The principal mechanical task of the matrix is to transmit the load to the fibers and to space them, with variable volumetric concentrations ranging from a small percentage to over 70%.

Low-level emissions may be generated by plastic deformation of the matrix or the fibers; however, during failure deformation the /9
so-called discharge signals generally predominate. With slow time

resolutions the individual peaks can be distinguished on the oscilloscope's path. This is the case with emissions due to discrete events with high energy content (about 10 volts greater than continuous emissions). Figure 7 shows the appearance of an oscilloscope path pertaining to a fracture test on a specimen of resin reinforced with glass.

The total duration of a discharge signal is determined by the multiple reflection of the material's acoustic impulses.

In the case of PRFV materials it is on the order of milliseconds. The sources of this high-level emission are essentially: a) bursting the fibers, b) cracking of the matrix, and c) failure of the fiber-matrix interface.

Very little has been said about the acoustic behavior of non-reinforced polymers, although Pollack [15] has described tests on glued aluminum joints, in which attempts were made to spot the damage at its onset in gluings that were prepared, if necessary, in a defective manner.

Curtis [19] instead has studied the acoustic responses of various kinds of fibers (glass, carbon, and polyacrylonitrile), which produce diverse frequency spectra when they are caused to fail. The predominant frequencies shift to higher values when the modulus of the fibers is increased.

Liptai [21] showed the influence of fiber orientation on A.E. response. He performed compression tests on cylindrical fiberglass and epoxy resin sheets. With the fibers oriented perpendicularly to the load axis, failure occurred at 45° to the axis, and the total number of signals increased progressively to the point of bursting, whereas the same material with fibers oriented parallel to the load axis yielded because of a single crack within the matrix, without traversing the fibers and pratically without warning on the part of A.E. signals, as shown in the diagram in Figure 8. /10

Rotem [22] studied A.E, from composites of epoxy resin reinforced with glass and carbon fibers, traction tested with different deformation speeds. He found that in the case of carbon only bursting of the fibers acted as an emission source, while in the case of glass, it could be either the fibers or the matrix. In the first case the A.E. trend was independent of the deformation rate, but this was not true in the second case. Such conclusions should be borne in mind when one wishes to set up a non-destructive testing procedure for fiber-reinforced materials, in as much as calibration of A.E. signals can be influenced by deformation rate.

3.1 Discrimination of Failure Mechanisms

In general, fiber-reinforced materials break in a complex manner through a combination of fracture of the fibers, cracking of the matrix, failure of the interface, or pull-out of the fibers.

An efficacious way of using A.E. techniques is discrimination between the various mechanisms, even when estimation of the A.E. data is extremely difficult.

Such a difficulty was noted by Speake and Curtis [18] in their attempt to correlate the frequency content of A.E. signals with the fracture processes in sheets of carbon fibers with epoxy matrix subjected to traction and torsion. In the intact sheets that were traction tested, yielding was essentially due to fiber failure, and the load-shift curve remained linear up to the failure. In these tests the A.E. fell within the frequency band of 0-70 kHz. In non-indented sheets in which fiber failure was preceded by cracks parallel to the fibers, the predominant frequency band was 30-130 kHz. In the torsion tests, compliance was at first due to plastic deformation of the matrix, followed by crack propagation parallel to the fibers and /11 finally by failure of the fibers, due to the very high levels of deformation. In these tests the predominant frequency band was 0-150 kHz.

Becht et al. [23] performed tests on various types of fiber-reinforced materials whose fracture processes were known, in order to discriminate among them by means of analysis of the the distribution of their signal amplitudes. The latter can be described [14] by an equation such as $I = I_o D^{-n}$, where I is the count rate, D is the preselected threshold level and I_o and n are positive constants. The authors determined the exponent for the different materials for each failure process, and observed that this exponent decreases as the energy released in the fracture process increases. In general, however, it happens only rarely that a single failure process occurs in a composite material, and this leads to a considerable variability in the values of n, and this complicates the determination of the predominant failure process in a material whose fracture behavior is unknown.

Notwithstanding the difficulties in discriminating between the different fracture mechanisms in the case where they occur simultaneously, we can still attempt to characterize them on the basis of results obtained by various experimenters.

3.1.1 Fiber Failure

Mehan and Mullin [24] in traction tests on sheets of epoxy resin containing only a few fibers, obtained results indicating that fracture of a fiber causes a sudden release of energy, which means that each failure of fiber can be correlated with a discharge of emissions. A similar correlation was obtained by Rathbun et al. [25] in traction on glass-resin composites containing a single strand.
However, in a composite structure the situation is complicated by /12
disalignment of fibers, simultaneous and multiple fiber failure, which factors make difficult the existence of a one to one correlation between fiber failure and emission discharges.

This point was confirmed by Rathbun et al. [25] in tests on spherical wound composite structures. They succeeded in identifying the region of failure with triangulation techniques, but they did not find a significant relationship between A.E. and number of broken fibers.

A significant relationship between fiber failure and A.E. in glass resin composites was obtained by Liptai [21], who found a very satisfying agreement between A.E. from an NOL specimen at 21° C and the cumulative fracture model proposed by Zweban and Rosen [20].

The mechanism of cumulative fracture is fundamentally an analysis of the sequence of events preceding the general failure; when the force applied increases, there will be a continuous increase in the dimensions and numbers of cracks as the fracture proceeds. The probability of at least one active crack also increases with the force applied. When the cracks reach a macroscopic level, a "continuous" approach can be used to define the fracture's propagation mechanism. With this model one can define the stress of failure, associating it with a particular probability and thus correlating the "continuous" theory of resistance to the material's structure.

This correlation did not hold at 79°C, which indicates either that the relation is no longer valid, or that a different failure process occurs at such temperatures.

Fitz-Randolph et al. [26] tested notched specimens by bending specimens with triangular boron/resin epoxy cross-sections, and noted the A.E. during the tests. They observed a series of load drops alternating with load upswings: during the former they /13
noted heavy discharges, associated with the increase in cracks, while weaker discharges were associated with the load upswings. The number of broken fibers was verified by measurement of electrical resistance and by a calibration technique for measuring the sheet compliance. Other relationships between total A.E. count and these observation techniques were obtained, and they all

had a practically linear behavior. Thus a relationship between A.E. counts and the number of fiber failures was indicated.

Balderston [27], in tests on notched specimens of boron epoxy resin found that A.E. coming from failure of fibers began at about 40% of the failure load. A similar premature response was observed by other experimenters with epoxy resins reinforced with glass and graphites. This behavior may be associated with the premature ailure of fibers due to disalignment and separation of the fiber-matrix interface.

Fuwa et al. [29], while studying the mechanisms of failure in plastic materials reinforced with carbon fibers, observed a notable similarity in the acoustic behavior during traction tests on non-indented or shaped specimens and 'bundles' of unattached carbon fibers from the matrix. Thus they were able to conclude that the source of A.E. signals was almost exclusively represented by the failure of the fibers, for which reason it was possible, in the case of intact specimens, to correlate A.E. data with the predominant type of damage and thus with the material's mechanical resistance.

This cannot be done in the case of indented specimens, since on the one hand the indentations do not affect the material's mechanical resistance (as noted by the authors): but on the other hand they do have various types of influence on the total number of emissions, because of damage within the matrix caused by the stress of cutting. This damage produces large quantities of low energy emissions that "flood" the high energy emissions /14
(correlated with failure of the fibers), causing confusion in the interpretation of the A.E. data. The authors obtained confirmation in this study of the validity of the Keiser effect: preloaded PRFC specimens did not emit until the maximum load previously applied was reached.

3.1.2 Fiber-Resin Separation

Mehan and Mullin [24], by identifying A.E. signals through failure events observed visually, established that the signals arising from fiber-resin separation are more gradual events than the sudden release of energy arising from failure of the fibers.

Dukes [30] provides data of complete counts, diagrammed as a function of the deformation, for polyester resins reinforced with glass, and polyester resins reinforced with glass, but with flexibility. He states that these counts come from separations or cracks in the resin, though he does not give direct evidence of the existence of these sources. The data, however, support his statement, because while the counts from ordinary resin display a stable count rate, those from the matrices which were made flexible display an initially low count rate, with a very rapid and sudden increase before the failure.

The changes in count rate before failure were also noted by Balderston [27], whose results include counts from fiber failure, fiber separation, and matrix failure. The count rate increases until shortly before the failure, at which point there is a decrease in rate followed by a rapid increase corresponding to the failure.

Similar variations in count rate were observed by Fitz-Randolph /15
et al. [26] for the same material. Their results, and their analysis in terms of fiber failure, have already been presented; these same results can also be analyzed in terms of fiber separation. The surface fracture energy had been measured by the work at fracture, the mechanics of elastic linear fracture, and the variation in compliance: a reasonable agreement was found among the values obtained by these diverse measurement techniques. The data on compliance were analyzed by finding the variation in surface fracture energy during propagation of the crack, and these values were compared with variations in the length of fiber pull-out and A.E. A notable

correlation was found: the total A.E. count per surface unit of the crack satisfied an almost linear relation with the surface fracture energy. The relationship between fiber pull-out length and crack area is of the same form as the total A.E. count per unit area of the crack, and the surface fracture energy, diagrammed as a function of the crack's area (Figure 9). Thus a relationship was established between fiber pull-out strength and A.E. count, which shows the importance of A.E. during pull-out.

3.1.3 Cracking of the Resin

Balderston [27] concluded, from tests on indented specimens of boron-resin epoxy, that failure of the resin is characterized by far lower discharges of energy than those arising from failure of the fibers.

Duke's results [30] may also contain signals arising from cracking of the resin, but the greater contribution from other processes makes it difficult to distinguish the role played by cracking of the resin. /16

Liptai [21] maintains that some systems in glass resin become degraded when subjected to fatigue, because of the onset and propagation of small cracks in the resin, where the high local concentrations of stress cause small yields in cohesion. The accumulation of these cracks obviously influences total A.E. count, as shown by intermittent static tests during fatigue tests on NOL wound specimens (Figure 8).

The works reviewed so far have indicated the use of A.E. techniques as a means of underst...ding the fracture behavior of composites by obtaining more precise and direct information on the microstructural processes of failure.

But our understanding of fracture behavior actually has two other main objectives: the realization, on the basis of A.E.

techniques, of testing methods for finished components <u>before</u> they enter service, and the possibility of establishing -- by means of A.E. readings -- the remaining life of components or structures subjected to fatigue, <u>during</u> service.

4. Fatigue Tests /17

The small resistance to cyclic mechanical wear is one of the factors that limit the use of fiber reinforced composites. In systems of fiber reinforced resin, the effects of the material's degradation are due to the onset and propagation of small cracks in the resin, where elevated local concentrations of stress cause small compliances in the cohesion. When the microfissures are multiplied and increased, the material's structural integrity is reduced, its properties of rigidity and resistance decrease, the Poisson ratio decreases, the resistance to chemical attack in general diminishes, and the optical and electrical behavior also generally deteriorates.

McGarry [32] used A.E. readings to show that cracks become extended according to the level of strain applied cyclically and according to the number of cycles imposed, a disproportionate amount of damage occurs in the first cycle. He asserts that cracking arises essentially because of a combination of fragility in the resin, contact and proximity among the fibers, and components of normal strain that act perpendicularly on fiber bundles.

Liptai [21] subjected DOL specimens (fiberglass and epoxy resin) to cyclic loading approximately equal to half their failure resistance, and tested them statically with intermittence at 3/4 of the failure load. The results, shown in Figure 10, indicate that A.E. increases as the fatigue cycles are increased. This type of analysis with static intermittent tests during the material's fatigue life can easily be applied to complex structures in order to evaluate the degradation of their material during service.

Fuwa et al. [34] in one of the papers that is part of a vast experimental program [7, 29, 33] studied the characteristics of A.E. arising from specimens of unidirectional carbon fibers in epoxy /18 resin subjected to cyclic loading. The results led to the conclusion that the damage produced in such specimens is of the same type as that produced during normal traction deformations, and that the A.E. trend during the first hundred load inversions in a cyclic test may indicate whether the specimen will break within a short time.

Williams and Reifsnider [28] fatigue-tested specimens of epoxy boron-resin and their results show a good relationship between the amount of damage to the specimen and the total number of acoustic signals, and also between the rate of development of the damage and the A.E. count rate.

Figure 11 shows a practically linear relation between total number of emissions and dynamic compliance of the structure.

5. Applications to Finished Components /19

A.E. techniques are easily adapted to examine simple or even complex structures made of composite materials, are relatively inexpensive, and require only a limited amount of time for acquisition of significant data. Analysis of the data is useful either to determine the operative mechanisms that govern fracture, or to evaluate the structural integrity of composite components that have been deformed in an unusual manner, in such a way as to create complex stress distributions.

Green et al. [31], using accelerometers, found a relationship of inverse proportionality between the energy released by the emissions and the failure pressure of chambers for wound missile engines. This was probably due to the fact that a smaller number of micro-failures occurred before general bursting in the vessel having the best properties, and thus there was higher failure pressure.

Becht et al. [23] studied the application of A.E. to the investigation of formation and propagation of artificially induced defects in PRFV wound pressure tubes. The emission from the defective tubes turned out to be rather more intense than that of the intact tubes. The authors conclude that it is possible to use A.E. for acceptance tests of tubes and vessels made of PRFV, by performing tests on well-defined specimens with and without defects, and comparing the results.

Incidentally, these authors confirmed the validity of the Keiser effect for PRFV materials. When the tubes were pressurized in two cycles, during the second cycle no signals were registered until the maximum cycle applied during the first cycle was reached.

Fuwa et al. [33], in A.E. tests on spherical pressure vessels made of wound carbon fibers in epoxy resin, found confirmation for /20 many of the conclusions toward which they were working, on flat specimens tested in traction, notwithstanding their structural complexity. This shows that the fibers in such vessels are subject to essentially the same solicitations as flat specimens. The results of this study suggest a possible testing method for such vessels in order to evaluate the maximum pressure they are capable of withstanding during service. If a vessel is pressurized and maintained at constant pressure for 10-20 minutes, the material practically becomes stabilized and stops emitting A.E. signals. If the vessel is then unloaded and repressurized, the pressure at which emissions recommence may be considered the maximum admissible working pressure.

Hamstad and Chiao [35] burst-tested wound pressure vessels and recorded the A.E. data.

The authors used organic and graphite fibers and two types of epoxy resin as a matrix. The results led them to the conclusion that A.E. techniques can furnish a method for determining the average density of fiber failure in correspondence with destruction of the vessel for various combinations of fibers and matrices, and that A.E. can distinguish defective vessels when the defects influence bursting of the vessel itself.

6. Conclusions

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The intent of this paper is to point out and illustrate the two main areas of application of A.E. techniques for materials in general and composites in particular: research on materials and evaluation of their structural integrity.

A.E. indeed may be either a method of physical measurement for attaining a deeper understanding of the fracture mechanisms acting upon materials, or a method of non-destructive control for detecting spreading defects.

We have presented experimental works that demonstrate definitively that failure in composite materials generates registrable acoustic emissions that can be correlated with microstructural fracture processes. These data can be obtained with experimental procedures that are easily adapted either to simple laboratory specimens or to complex structures, inexpensively and with only a limited amount of time needed for acquisition and analysis of data. On the basis of the laboratory results it has been established that analysis by A.E. can be applied to the problem of evaluating structural integrity, and some examples have been reviewed (discrimination between intact pressure vessels vs. those containing critical cracks, location of critical zones by triangulation techniques, continuous control during service, etc.).

A.E. techniques provide results not attainable -- or attainable only with much time and expense -- by other techniques. The advantages and limitations of A.E. can be summarized as follows.

Advantages

a) detecting and localizing defects from a distance;
b) increased sensitivity;
c) rapid installation, and speedy analysis of data;
d) 100% inspection of the structure. /22

Limitations

a) requires application of a strain;
b) strongly depends on the material and its geometry;
c) spurious emissions must be eliminated.

If one bears in mind that the standard methods of non-destructive control, such as radiographic and ultrasonic examination, are not able to detect certain defects in composite materials; and that since many composites are non-metallic, magnetic and parasitic current techniques usually cannot be applied, it seems convincing that A.E. is destined to acquire a stable position within the next decade among the non-destructive techniques universally accepted for routine inspection of composite materials.

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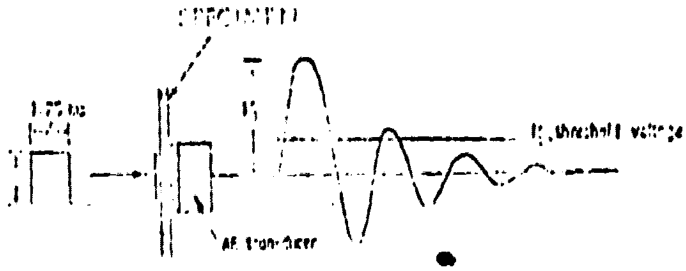

Figure 1. Signal produced by the transducer in response to a single A.E. impulse.

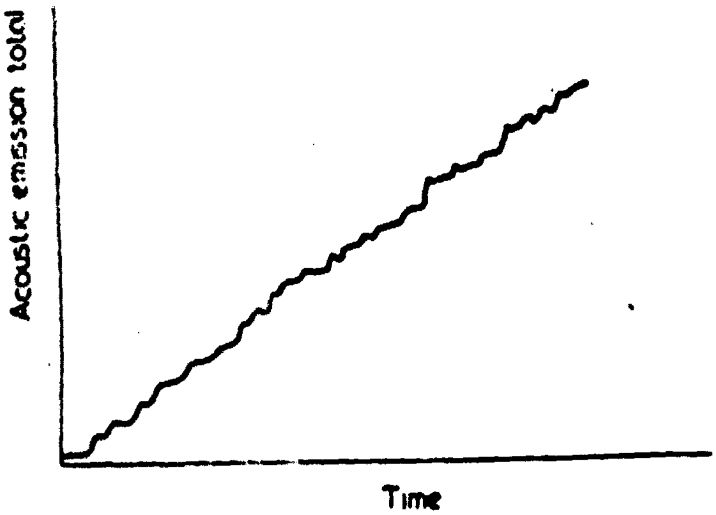

Figure 2. Acoustic emissions of the continuous type.

Fig. 3. Total Acoustic Emissions

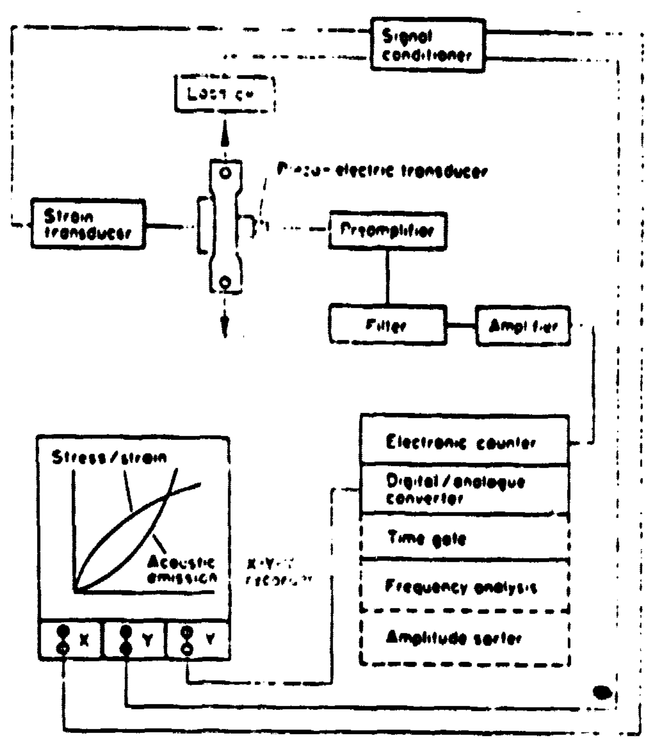

Fig. 4. Block scheme of a typical A.E. detection system

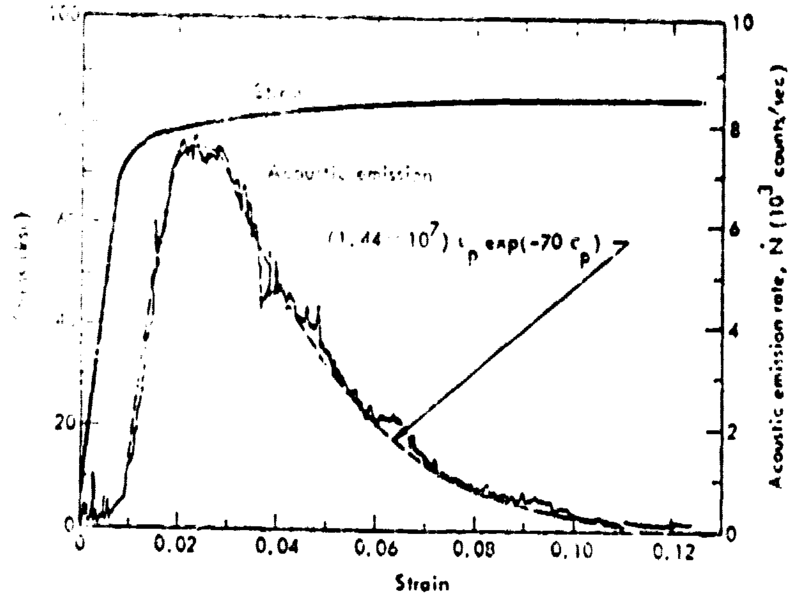

Figure 5. A.E. and stress as a function of deformation for 70765-T6 aluminum specimens tested in traction. The hatched curve represents Gilman's theoretical expression for the density of mobile dislocations as a function of the plastic deformation.

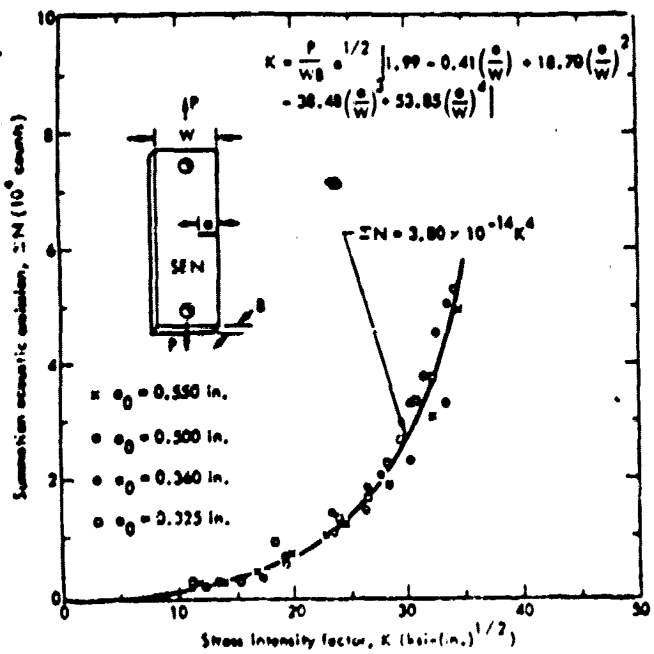

Figure 6. Total A.E. count as a function of the stress intensity factor for four laterally notched specimens with different crack lengths.

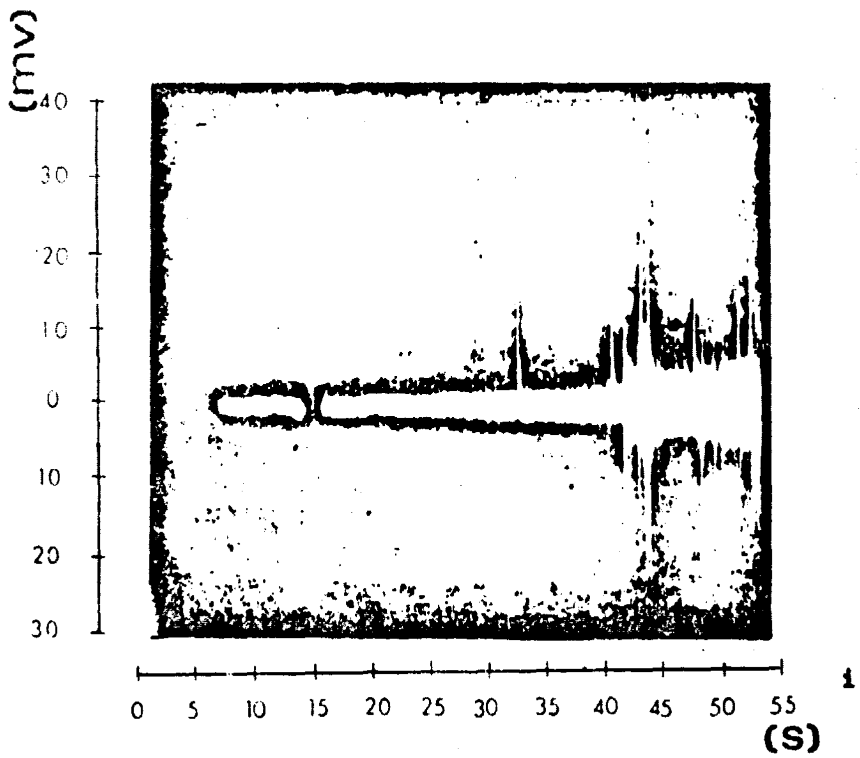

Figure 7. Oscilloscope path made by signals in a failure test with traction on a glass resin specimen.

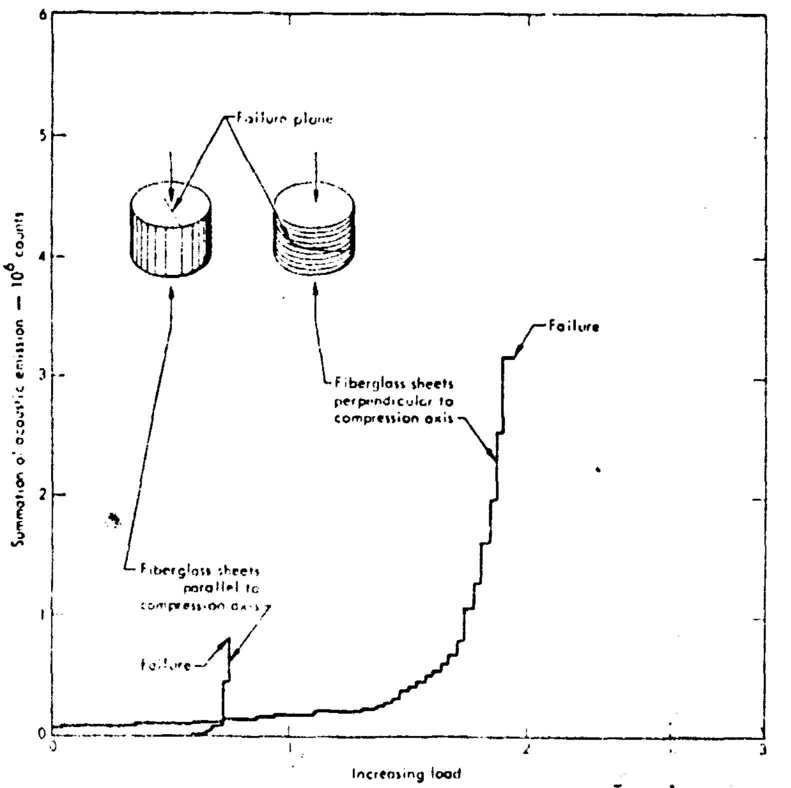

Figure 8. Total A.E. count as a function of load for cylindrical sheets of fiberglass and epoxy resin. The results pertain to fibers perpendicular and parallel to the load (compression) axis.

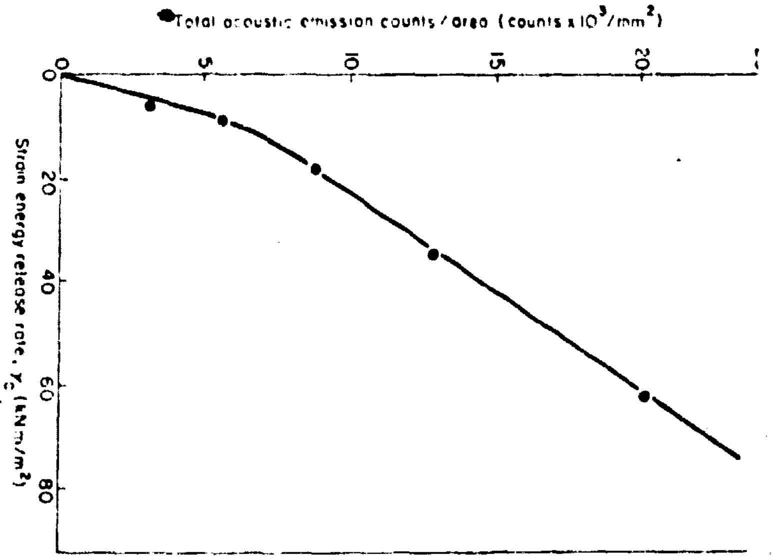

Figure 9. Variation of total A.E. count with the release rate of deformation energy.

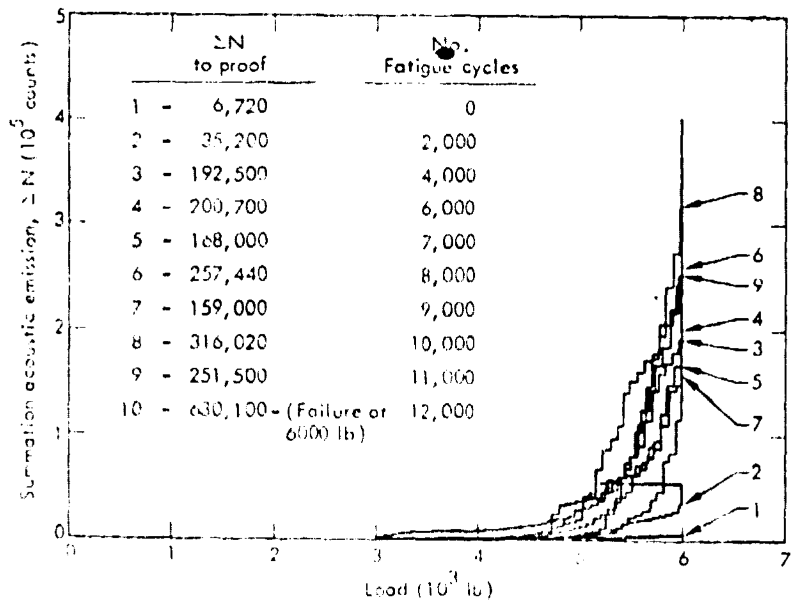

Figure 10. Total A.E. count as a function of the load applied to an NOL specimen. The specimen was subjected to cyclic loading of 4,000 lbs and tested statically with intermittence at a load of 6,000 lbs.

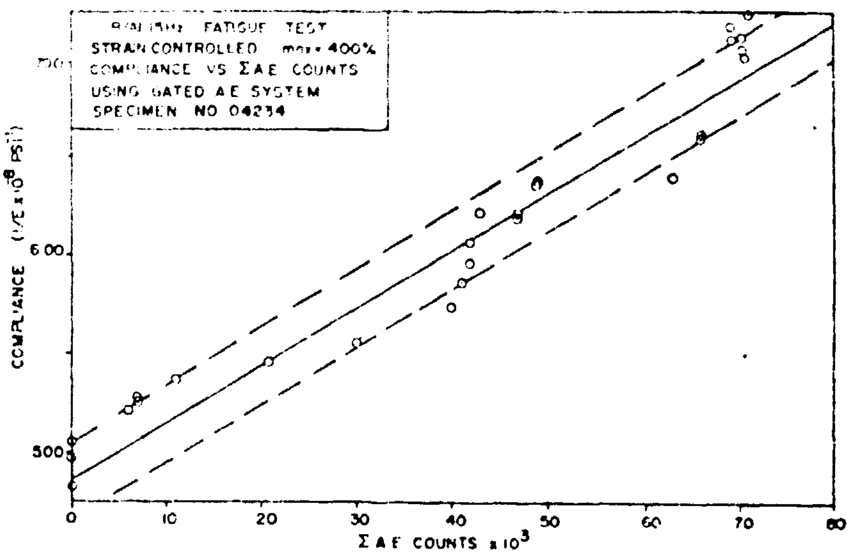

Figure 11. Compliance of the specimen diagrammed as a function of total A.E. count.