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Selecting a Nondestructive Testing Method, Part VII: Acoustic Emission Testing

INTRODUCTION

Acoustic emission testing (AET) is a nondestructive technique that monitors defect formation and failure within a material through the detection and analysis of acoustic emission (AE) signals – stress waves generated by the rapid release of strain energy.[1, 2] External stimuli, such as a temperature gradient or an in-service mechanical load, can cause changes to the internal structure of a material. Crack initiation and propagation (release of stored elastic energy), the opening and closing of cracks, twinning*, dislocation movement (i.e., slip), reorientation of grain boundaries, plastic deformation, and phase transformations (release of stored chemical and/or free energy) all lead to the release of AE signals.[1-6] AET is fundamentally different from other nondestructive testing (NDT) methods because it passively detects energy that is released from a material, whereas other methods require an energy input for the defect to be detected (i.e., x-rays, gamma rays, ultrasound, thermal energy, and microwaves).[2]

AET is effective for detecting fatigue and fracture behaviors in metals, composites, plastics, fiberglass, ceramics, concrete, and wood and is commonly used for the detection of faults and/or leaks in pressure vessels, piping systems, and tanks and to monitor welding and corrosion progress.[1, 2, 7] As welds solidify, acoustic emissions are released and detected as a result of internal structural changes; these emissions stop when the welded joint is completely hardened. Corrosion, on the other hand, is detectable since it is a chemical reaction that involves the release of energy. This energy can be detected by AE sensors and as a result, corrosion progress can be tracked.

HISTORY AND RECENT ADVANCEMENTS

Acoustic emissions were first discovered over a century ago by researchers who had reported hearing audible sounds while performing experiments with metals, specifically tin. Tin deformation produced what is known as a tin-cry, later found to be a result of twinning.

Professor Fuyuhiko Kishinouye was the first to report on a scientifically planned experiment with acoustic emission during the 1933 meeting of the Earthquake Research Institute. He conducted a series of experiments that amplified and recorded the acoustic emissions produced by wood fracture during earthquakes, providing a much needed route for solving problems related to the time distribution of earthquakes. This work was followed in 1936 by Dr. Friedrich Förster and Erich Scheil, who published the results of their first AE experiments with nickel-steel.[8]

Nevertheless, the major efforts initiated in 1950, pertaining to the fundamentals of AE phenomenon and behavior during fracture and deformation, have led this year to be recognized as the most significant in the history of AE. This age of great advancement began in Germany with the research of Joseph Kaiser and continued to expand through the 1950s and 60s. (The US initiated its first major AE effort in 1954.) Instrumentation for AE was developed during this period, and the characterization of AE behavior in many materials was completed. At the same time, AE was gaining recognition for its unique capabilities in monitoring dynamic processes.[8]

During the late 1960s and 1970s, the AE Working Group was formed to encourage the exchange of ideas and information related to AET on an international scale, and to set a direction for future AE research. Work during this period focused on the formation and movement of dislocations as a source of AE and led to one of the most cited research papers in AE, written by D.R. James and S.H. Carpenter on the Thiokol Vessel Failure. AE instrumentation also became commercially available during this period.[8]

The end of the Cold War in the 1980s saw a decline in the number of nuclear reactors and heavy machinery. Because these areas were the most promising for AE applications, their decline caused a reduction in AE research spending. However, with the computer becoming a basic component for instrumentation and data analysis during the later part of the decade, new opportunities for research and development emerged. During the mid-1990s, AE was applied extensively in the petrochemical and aerospace industries.[8]

Currently, AE is a well-established and reliable technique for monitoring the condition of and damage in a range of structures and has emerged as a powerful technique in NDT. This increase in popularity can be attributed to recent advances in AE instrumentation, specifically high-speed digital waveform-based AE instrumentation, which enables large numbers of AE waveform signals to be digitized and stored.[9]

BASIC PRINCIPLES

AET is a continuous testing process that does not require the disassembly of a structure or sample for testing, as is common practice with ultrasonic and x-ray NDT, since it is carried out on an entire structure under its in-service loading.[1, 4, 10] If defects are present, AE sensors will detect the defect propagation as the acoustic emissions produced travel away from the source.[11] These AE signals† are collected by stationary piezoelectric sensors and subsequently measured and amplified (Figure 1). [10-13] Piezoelectric sensors are critical to AET because they convert the mechanical AE waves into electrical voltages. These AE sensors operate in the frequency range from 1-1200 kHz, detecting acoustic energy at frequencies far below and far above the audible range.[4, 12, 14] The electrical signals generated by the piezoelectric sensors are output to equipment for processing and later displayed for interpretation.[10-13] As the discontinuity or defect approaches a critical size, the AE count rate will increase to warn of an impending instability and failure.[2] (The rate at which acoustic emissions are produced is directly related to the microstructure and deformation mode of the material. For instance, brittle or homoge-

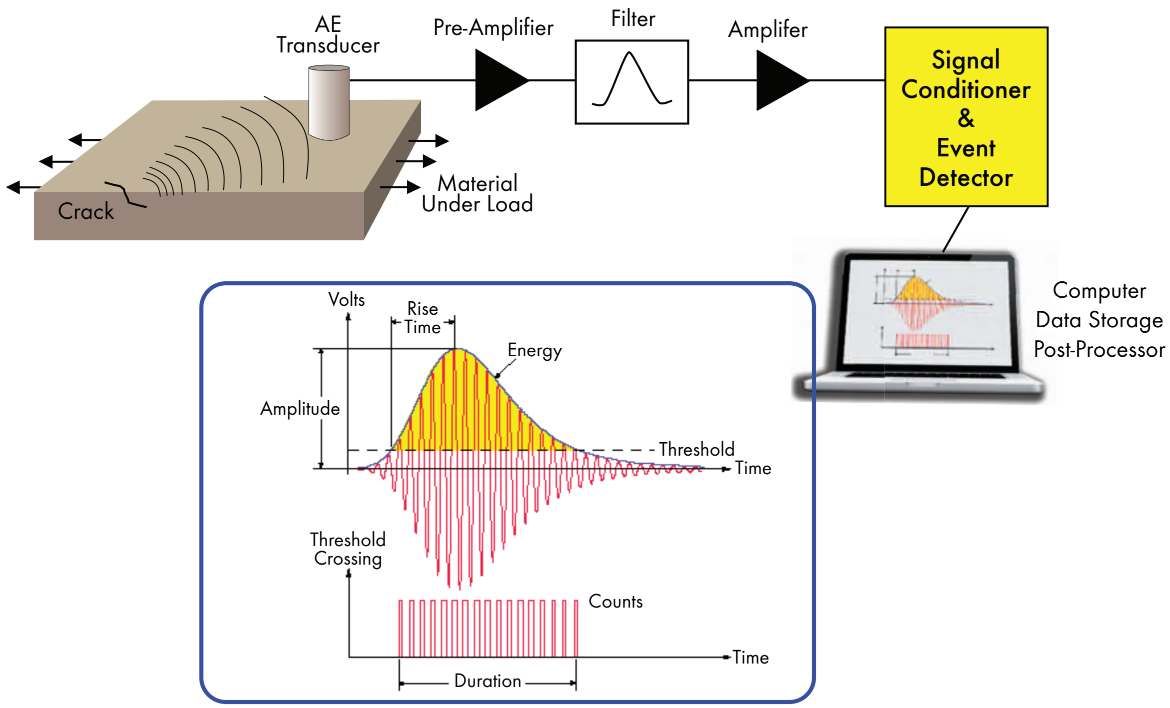

Figure 1. **A basic AE test set-up and sample output.**

neous materials are more likely to emit large quantities of AE, whereas materials with ductile deformation mechanisms emit fewer AE.[4])

When setting up an acoustic emissions test, material loading is crucial. AET is typically performed on in-use structures using an array of sensors, since the in-service loading applies enough stress to cause the already present defects to propagate.[12] Performing AET on in-service structures requires the addition of sensors only; these sensors do not cause the defect to propagate since they apply no additional external stimuli. Simply put, AET detects already present defects, defects that would grow whether AE sensors were connected to the structure or not. For this reason, AET is considered a NDT method.

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An important feature of AET is its irreversibility; if the material is loaded to a given stress level, unloaded, and reloaded, no emissions will be noted upon reloading unless the previous loading has been exceeded or further damage is present.[2] Until this point the material will behave elastically. This behavior is referred to as the Kaiser Effect and directly results from the fact that AE are closely related to plastic deformation and fracture.[2] This irreversibility has important practical considerations and is the reason AET detects already present flaws.[1, 2, 4]

AET exploits the Kaiser Effect as a means for determining the stress at which damage occurs. As damage accumulates from continued use, the Kaiser Effect breaks down (i.e., acoustic emissions are detected at lower stress levels). This is known as the Felicity Effect. The Felicity Ratio is used to denote the percentage of full-loading (or maximum previous loading) at which the first AE are detected. For example, if acoustic emissions are detected at 93% of the rated usage load or previous loading, the Felicity Ratio would be 9.3. As this number decreases, the likeliness of a structure to have severe damage increases.

INSPECTION REQUIREMENTS

By monitoring acoustic emissions, inspectors can locate specific regions where anomalies are likely to be found in a nonintrusive manner. To ensure that these inspections are correctly performed, proper equipment and qualified personnel are required to evaluate and interpret the results. [4, 5]

As shown in Figure 1, typical AET setups include sensors, preamplifiers, filters, and amplifiers. Additional equipment (i.e., oscilloscopes, voltmeters, and computers) is regularly required to aid in collecting, storing, and analyzing the data. [4, 5] The sensors used are typically of a resonance type (Figure 2), being designed to operate within a specific, narrow frequency range, resulting in the production of weak acoustic emission signals. For this reason, a preamplifier is used to minimize the noise‡ interference and prevent signal loss. Since this is a frequently encountered issue, the transducer and preamplifier are sometimes built as a unit to allow the signals to be filtered and excess noise removed. Once the noise has been removed from the

The term acoustic emission is a slight misnomer since the name implies an emission within the audible range. Throughout history, however, acoustic emissions testing has evolved as new equipment was developed. With this evolution, acoustic emissions testing has changed, enabling the detection of emissions above and below the audible range. On average, acoustic emissions testing detects emissions within the frequency range from 20-1200 kHz [4]. Audible emissions are produced between 20 Hz and 20 kHz, contradicting the term acoustic. Nevertheless, when first discovered and named, the emissions detected were audible, supporting the acoustic emissions name. And although the meaning has changed over time as technologies have improved, the name has not.

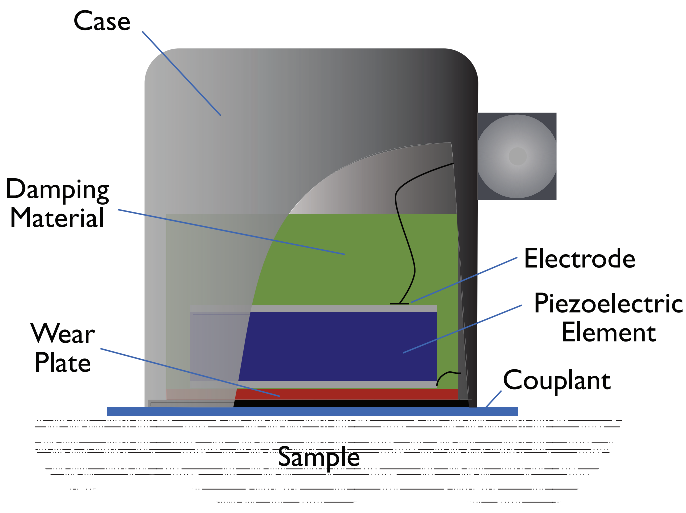

Figure 2. Acoustic emission testing transducer.

signal, it is amplified and subsequently sent to the signal conditioner where it is further transferred to a data output and storage device.[1]

In addition to recording and analyzing the output AE data, it is also important to note the loading, deformation, pressure, and temperature of the structure at the time of the testing for future reference.[1]

PRACTICAL CONSIDERATIONS

AE differs from other nondestructive testing techniques in two ways. First, AET is a method used to detect the signals emitted from a material or structure under an in-service load. In other words, no energy is applied to the material; rather the energy is released from the material. Conversely, other NDT methods require energy to be applied to the test sample prior to defect analysis. Secondly, AE deals with dynamic changes within a material as opposed to the detection of static defects. Therefore, it can be used to differentiate between static and active defects§.[4, 5]

AE waves are most easily detected when a loaded material undergoes plastic deformation or when a material is loaded up to, or near, its maximum yield stress. However, the applied stress should not exceed the load ratings; thus, it should not be great enoughto cause deformation.[2] To avoid these potential issues, AET is preformed on an in-use or in-service structure. With the proper equipment, setup, and trained personnel, stress waves indicating flaws on the order of micrometers** can be observed. Despite this sensitivity AE systems, when used alone, can only qualitatively determine the extent of damage to a structure. Therefore, it is necessary to have knowledge of the situations in which AET is advantageous and when it is not to adequately assess the given structure or material for flaws. [4, 5]

AET Advantages

AET is advantageous when compared to other NDT methods since it is the only proven method for detecting cracks in metals that does not require the sensor to be placed directly over the crack; it can be done without taking the structure out of operation; it provides a way to detect dynamic changes; no energy has to be supplied to the test object; it allows a complete integrity analysis to be done in a fast, one-step process; sensors can be placed permanently for remote monitoring; and it can be used to detect flaws in areas that are inaccessible using other NDT methods.[4, 5, 12]

Limitations of AET

Although AET has numerous applications, there are instances where its use may be complex, such as its use on large structures. When testing large structures, significant numbers of sensors and instrumentation channels are required. This may be a hindrance, and in some cases inhibit the use of AET. These sensor and instrumentation channel requirements are directly correlated to the potential for large numbers of damage sites and for locations that experience no to low stress.[15]

Additionally, extraneous, external stimuli have also been shown to be a hindrance to obtaining good results during AET. Unlike other NDT methods, AE is a real-time test that is sensitive to local instabilities, or noise, at the testing site. Noise is caused by frictional sources such as loose bolts, impact sources such as rain, flying debris, or dust blown by the wind, and the mechanical vibrations of equipment (i.e., pumps) in the surrounding area. Although noise is not a prohibitive issue for AET, it is an issue that has to be accounted for before the results can be interpreted. In fact, testing personnel have a number of proven testing procedures available to them that can be used to compensate for any background noise picked up by the sensors. The most common approaches include fabricating sensors with electronic gates to block the noise, placing sensors as far away from the noise sources as possible, and electronic filtering††.[4, 5]

Aside from noise and sensor quantities, the third greatest concern when using AET is the lack of quantitative results. If a particular effort requires specific, quantitative results on the size, depth, or the overall condition of a material, AET is not the appropriate method as it is not able to supply this information. For this reason, other NDT methods are needed and can be used to supplement any AET results. The NDT method selected is strongly dependent upon the material and application.[4, 5]

AET Summary [2, 4, 17]

Discontinuity types (e.g., what types the method can detect)	• Cracks • Plastic Deformation • Phase Transformations	• Leak Monitoring • Dislocations • Corrosion
Size of discontinuities	• Detects changing flaws, not static ones • Gross occurrences that produce audible signals to micro-occurrences such as movements of dislocations • One order of magnitude smaller than those detected by other NDT methods	
Limitations	• Material must be under a mechanical or thermal stress (in-service) • External noise	
Advantages	• Provides complete integrity analysis of a structure • Dynamic inspection tool-measures the response of a discontinuity to an imposed stress • Can detect and evaluate the structural significance of flaws that may be inaccessible to other traditional NDI methods • Requires limited access and downtime for the requalification of in-service structures • Can be used to limit the maximum pressure during pressure testing and to prevent failure if the structure contains a significant discontinuity • Non-directional: no prior knowledge of probable location and orientation of defect required • Can be used on composites and ceramics as well as metals, concrete, plastic, fiberglass	
Inspector training (level and/or availability)	• Training available – ASNT Level III	
Inspector certification required	• Strongly recommended to ensure reliable results	
Equipment	• Sensor-Piezoelectric Transducer • Pre-Amplifier • Filter	• Amplifier • Data Display/Storage Device
Relative cost of inspection	• Varies according to application or structure being inspected	

Example DoD Applications of AE

The DoD has employed AET across a wide variety of systems and components. AET has been used to monitor flaws on ships, aircraft, and ground vehicles. The periodic monitoring of a given flaw using AET allows system maintainers to compare the data for a particular flaw to known growth rates for the same emission level and subsequently determine if the flaw of interest is critical. With specific knowledge on the severity of a flaw, the maintainer can evaluate its impact on the service life of the system.[16]

Figure 3. **Acoustic emissions testing being used to monitor a fire hydrant for leaks. (Photo courtesy of U.S. Army Corps of Engineers.)[16]**

The US Army Corps of Engineers has used a form of AET, referred to as acoustic leak detection (ALD), to detect leaks in the potable water systems at multiple CONUS‡‡ installations. Results of this effort have shown that ALD is an extremely accurate method to determine the exact leak location in long piping systems. A high return-on-investment for the ALD equipment was realized along with potential configurations that allow for permanent monitoring with remote data collection and analysis.[16] Figure 3 shows an ALD application as applied to a fire hydrant.

CONCLUSION

AET is a nondestructive test method that, without the input of energy, enables the detection of acoustic energy released from a physical or mechanical change within a material. AET is highly effective when used to detect fatigue and fracture behavior in metals, composites, plastics, fiberglass, ceramics, concrete, and wood. With the proper equipment, setup, and trained personnel, AET can detect flaws on a micrometer scale. Its numerous advantages and uses have made AET a well-established and reliable NDT technique for monitoring condition and damage in a range of structures for the prevention of material failures. This method can help avoid costs associated with repairs to damaged structures if a defect were to go undetected.

NOTES & REFERENCES

* Twinning can occur during the growth of a crystal or when it is subjected to stress. Stresses may result from temperature and/ or pressure conditions that differ from those in which the crystal was originally formed. Twinning is the result of two or more inter-grown crystals that formed in a symmetric fashion.[3]

† There are two major types of AE signals: continuous and burst. With continuous AE the amplitude of the signal varies with AE activity. In metals and other alloys, this behavior is thought to be associated with dislocation movements within the grains. Burst AE are short duration pulses associated with the release of discrete strain energy. The amplitude of a burst AE is greater than that of a continuous AE.[2]

‡ Noise is any signal picked up by the AE sensor that is unrelated to the defect propagation.

§ AE can be used to detect stagnant defects by comparing AET results to the results from previous AE tests if the data is available (this is uncommon since this type of data is not usually available).

** 1 Micrometer = 1 x 10^{-6} meters

†† Electronic filtering uses signal arrival times or differences in spectral content to differentiate between AE signal data and background noise.

‡‡ CONUS is an acronym that stands for the Continental United States.

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