برنامه نویسی

مرکز دانلود رایگان
مهندسی متالورژی و مواد

www.Iran-mavad.com
Acoustic Emission Method


Dr. Boris Muravin
Outline

1. Acoustic Emission phenomena.
2. History of Acoustic Emission from Stone Age to these days.
3. AE instrumentation:
   1. Sensors, preamplifiers, cables (types, specific applications).
   2. Data Acquisition systems (analog and digital, signal digitation, filtration).
4. Principals of AE data measurement and analysis.
6. AE in metals.
7. Relationship between AE and fracture mechanics parameters and effects of AE.
8. AE applications.
10. Conclusions.
Definition of Acoustic Emission Phenomenon

Acoustic Emission is a phenomenon of sound and ultrasound wave radiation in materials undergo deformation and fracture processes.
Who was the First?

He was the First who used AE as a forecasting tool

They were the First who used AE as an alarm system
Early History of AE

The sound of a cry from Babylon and the sound of great fracture <comes> from the land of the Chaldeans.

Jeremiah 51:54

▶ One of the first sources that associates sound with fracture can be found in the Bible.
▶ Probably the first practical use of AE was by pottery makers, thousands of years before recorded history, to assess the quality of their products.
▶ Probably the first observation of AE in metal was during twinning of pure tin as early as 3700 B.C.
▶ The first documented observation of AE in Middle Ages was made by an Arabian alchemist, Geber, in the eighth century. Geber described the “harsh sound or crashing noise” emitted from tin. He also describes iron as “sounding much” during forging.
History of First AE Experiments

- In 1920, Abram Joffe (Russia) observed the noise generated by deformation process of Salt and Zinc crystals. “The Physics of Crystals”, 1928.
- In 1936, Friedrich Forster and Erich Scheil (Germany) conducted experiments that measured small voltage and resistance variations caused by sudden strain movements caused by martensitic transformations.
- In 1948, Warren P. Mason, Herbert J. McSkimin and William Shockley (United States) suggested measuring AE to observe the moving dislocations by means of the stress waves they generated.
- In 1950, D.J Millard (United Kingdom) performed twinning experiments on single crystal wires of cadmium. The twinning was detected using a rochelle salt transducer.
History of First AE Experiments

- In 1950, Josef Kaiser (Germany) used tensile tests to determine the characteristics of AE in engineering materials. The result from his investigation was the observation of the irreversibility phenomenon that now bears his name, the Kaiser Effect.

- The first extensive research after Kaiser was done in the United States by Bradford H. Schofield in 1954. Schofield investigated the application of AE in the field of materials engineering and the source of AE. He concluded that AE is mainly a volume effect and not a surface effect.

- In 1957, Clement A. Tatro, after performing extensive laboratory studies, suggested to use AE as a method to study the problems of behavior of engineering metals. He also foresaw the use of AE as an NDT method.
Start of Industrial Application of AE

- The first AE test in USA was conducted in the Aerospace industry to verify the integrity of the Polaris rocket motor for the U.S Navy (1961). After noticing audible sounds during hydrostatic testing it was decided to test the rocket using contact microphones, a tape recorder and sound level analysis equipment.

- In 1963, Dunegan suggested the use of AE for examination of high pressure vessels.

- In early 1965, at the National Reactor Testing Station, researchers were looking for a NDT method for detecting the loss of coolant in a nuclear reactor. Acoustic Emission was applied successfully.

- In 1969, Dunegan founded the first company that specializes in the production of AE equipment.

- Today, AE Non-Destructive Testing used practically in all industries around the world for different types of structures and materials.
Acoustic Emission Instrumentation

Typical AE apparatus consist of the following components:
- **Sensors** used to detect AE events.
- **Preamplifiers** amplifies initial signal. Typical amplification gain is 40 or 60 dB.
- **Cables** transfer signals on distances up to 200m to AE devices. Cables are typically of coaxial type.
- **Data acquisition device** performs filtration, signals’ parameters evaluation, data analysis and charting.
AE Sensors

- Purpose of AE sensors is to detect stress waves motion that cause a local dynamic material displacement and convert this displacement to an electrical signal.

- AE sensors are typically piezoelectric sensors with elements made of special ceramic elements like lead zirconate titanate (PZT). Mechanical strain of a piezo element generates an electric signal.

- Sensors may have internally installed preamplifier (integral sensors).

- Other types of sensors include capacitive transducers, laser interferometers.

Regular piezoelectric sensor | Preamplifier 60 dB | Integral piezoelectric sensor
Sensors Characteristics

- Typical frequency range in AE applications varies between 20 kHz and 1 MHz.
- Selection of a specific sensor depends on the application and type of flaws to be revealed.
- There are two qualitative type of sensor according to their frequency responds: resonant and wideband sensors.
- Thickness of piezoelectric element defines the resonance frequency of sensor.
- Diameter defines the area over which the sensor averages surface motion.
- Another important property of AE sensors includes Curie Point, the temperature under which piezoelectric element loses permanently its piezoelectric properties. Curie temperature varies for different ceramics from 120 to 400°C. There are ceramics with over 1200°C Curie temperature.

AE signal of lead break and corresponding Power spectrum.
Installation of Sensors on Structure

Type of installation and choice of couplant material is defined by a specifics of application.

- Glue (superglue type) is commonly used for piping inspections.
- Magnets usually used to hold sensors on metal pressure vessels. Grease and oil then used as a couplant.
- Bands used for mechanical attachment of sensors in long term applications.
- Waveguides (welded or mechanically attached) used in high temperature applications.
- Rolling sensors are used for inspection rotating structures.
- Special Pb blankets used to protect sensors in nuclear industry.
Methods of AE Sensors Calibration

- The calibration of a sensor is the measurement of its voltage output into an established electrical load for a given mechanical input. Calibration results can be expressed either as frequency response or as an impulse response.

- Surface calibration or Rayleigh calibration: The sensor and the source are located on the same plane surface of the test block. The energy at the sensor travels at the Rayleigh speed and the calibration is influenced by the aperture effect.

\[ U(t) = \frac{1}{A} \int_{S} u(x, y, t) r(x, y) dx dy \]

- Aperture Effect:
  - \( r(x, y) \) – local sensitivity of the transducer face
  - \( S \) – region \((m^2)\) of the surface contacted by the sensor
  - \( A \) – area of region \( S \)
  - \( u(x, y, t) \) – displacement \((m)\) of the surface

- Through pulse calibration: The sensor and the source are coaxially located on opposite parallel surfaces. All wave motion is free of any aperture effect.
AE Data Acquisition Devices

Example of AE device parameters:

- 16 bit, 10 MHz A/D converter.
- Maximum signal amplitude 100 dB AE.
- 4 High Pass filters for each channel with a range from 10 KHz to 200 KHz (under software control).
- 4 Low Pass filters for each channel with a range from 100 KHz to 2.1 MHz (under software control).
- 32 bit Digital Signal Processor.
- 1 Mbyte DSP and Waveform buffer.
Principals of AE Data Measurement and Analysis
Threshold and Hit Definition Time (HDT)

Threshold and HDT are parameters that are used for detection AE signals in traditional AE devices. HDT: Enables the system to determine the end of a hit, close out the measurement process and store the measured attributes of the signal.
Burst and Continuous AE Signals

*Burst AE* is a qualitative description of the discrete signal's related to individual emission events occurring within the material.

*Continuous AE* is a qualitative description of the sustained signal produced by time-overlapping signals.

“AE Testing Fundamentals, Equipment, Applications” , H. Vallen
AE Parameters

- Peak amplitude - The maximum of AE signal.
  \[ \text{dB} = 20 \log_{10} \left( \frac{V_{\text{max}}}{1 \mu\text{volt}} \right) - \text{preamplifier gain} \]
- Energy - Integral of the rectified voltage signal over the duration of the AE hit.
- Duration - The time from the first threshold crossing to the end of the last threshold crossing.
- Counts - The number of AE signal exceeds threshold.
- Average Frequency - Determines the average frequency in kHz over the entire AE hit.
  \[ AF = \frac{AE \text{ counts}}{Duration} \ [kHz] \]
- Rise time - The time from the first threshold crossing to the maximum amplitude.
- Count rate - Number of counts per time unit.
Background Noise

Background Noise: Signals produced by causes other than acoustic emission and are not relevant to the purpose of the test.

Types of noise:
- Hydraulic noise - Cavitations, turbulent flows, boiling of fluids and leaks.
- Mechanical noise - Movement of mechanical parts in contact with the structure e.g. fretting of pressure vessels against their supports caused by elastic expansion under pressure.
- Cyclic noise - Repetitive noise such as that from reciprocating or rotating machinery.
- Electro-magnetic noise.

Control of noise sources:
- Rise Time Discriminator - There is significant difference between rise time of mechanical noise and acoustic emission.
- Frequency Discriminator - The frequency of mechanical noise is usually lower than an acoustic emission burst from cracks.
- Floating Threshold or Smart Threshold - Varies with time as a function of noise output. Used to distinguish between the background noise and acoustic emission events under conditions of high, varying background noise.

Master – Slave Technique – Master sensor are mounted near the area of interest and are surrounded by slave or guard sensors. The guard sensors eliminate noise that are generated from outside the area of interest.
Attenuation, Dispersion, Diffraction and Scattering Phenomena

The following phenomena take place as AE wave propagate along the structure:

- **Attenuation**: The decrease in AE amplitude as a stress wave propagate along a structure due to Energy loss mechanisms, from dispersion, diffraction or scattering.

- **Dispersion**: A phenomenon caused by the frequency dependence of speed for waves. Sound waves are composed of different frequencies hence the speed of the wave differs for different frequency spectrums.

- **Diffraction**: The spreading or bending of waves passing through an aperture or around the edge of a barrier.

- **Scattering**: The dispersion, deflection of waves encountering a discontinuity in the material such as holes, sharp edges, cracks inclusions etc....

- Attenuation tests have to be performed on the actual structures during their inspection.

- The attenuation curves allows to estimate amplitude or energy of a signal at the at the given the distance from the sensor.
Source Location
Source Location Concepts

- Time difference based on threshold crossing.
- Cross-correlation time difference.
- Zone location.
Linear Location

- Linear location is a time difference method commonly used to locate AE source on linear structures such as pipes. It is based on the arrival time difference between two sensors for known velocity.

- Sound velocity evaluated by generating signals at known distances.

\[
d = \frac{1}{2} \left( D - \Delta T \cdot V \right)
\]

where:
- \( d \) = distance from first hit sensor
- \( D \) = distance between sensors
- \( V \) = wave velocity

### Table: Effective velocity in a thin rod [m/s]

<table>
<thead>
<tr>
<th>Material</th>
<th>Effective velocity in a thin rod [m/s]</th>
<th>Shear [m/s]</th>
<th>Longitudinal [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brass</td>
<td>3480</td>
<td>2029</td>
<td>4280</td>
</tr>
<tr>
<td>Steel 347</td>
<td>5000</td>
<td>3089</td>
<td>5739</td>
</tr>
<tr>
<td>Aluminum</td>
<td>5000</td>
<td>3129</td>
<td>6319</td>
</tr>
</tbody>
</table>
For location of an AE source on a plane two sensors are used. The source is situated on a hyperbola.

\[ \Delta t_{12} V = R_1 - R_2 \]
\[ Z = R_1 \sin \theta \]
\[ Z^2 = R_1^2 - (D - R_2)^2 \to R_2^2 \sin^2 \theta = R_1^2 - (D - R_2 \cos \theta)^2 \]
\[ R_2^2 = R_1^2 - D^2 + 2D \cos \theta \]
\[ R_1 = \Delta t_{12} V + R_2 \]
\[ \Rightarrow R_2 = \frac{1}{2} \frac{D^2 - \Delta t_{12}^2 V^2}{\Delta t_{12} V + D \cos \theta} \]

- Distance between sensor 1 and 2
- Distance between sensor 1 and source
- Distance between sensor 2 and source
- Time difference between sensor 1 and 2
- Angle between lines \( R_2 \) and \( D \)

Three sensors are used to locate a source to a point by intersecting two hyperbolae using the same technique as two sensors.
Cross-correlation based Location

Cross-correlation function

\[
C(t) = \int S_{Ch1}(\tau) \cdot S_{Ch2}(\tau + t) \, dt
\]

\[
\Delta t = t|_{\max\{C(t)\}}
\]

Cross-correlation method is typically applied for location of continuous AE signals.
Zone Location

- Zone location is based on the principle that the sensor with the highest amplitude or energy output will be closest to the source.
- Zonal location aims to trace the waves to a specific zone or region around a sensor.
- Zones can be lengths, areas or volumes depending on the dimensions of the array.
- With additional sensors added, a sequence of signals can be detected giving a more accurate result using time differences and attenuation characteristics of the wave.
Acoustic Emission in Metals
Sources of AE in Metals

Major macroscopic sources
of AE in metals are: crack jumps, plastic deformation development, fracturing and de-bonding of hard inclusions.

Microscopic sources
includes dislocation movement, interaction, annihilation, slip formation, voids nucleation, growth and interaction and many other.

More then 80% of energy expended on fracture in common industrial metals goes to development of plastic deformation.

Possible combinations

| AE SOURCES | 6.9 \times 10^{236} |

---

nucleation development branching
nucleation growth interaction
bond connection fracturing
fracturing crack formation
Inclusions
Dislocations
Micro-crack
Voids
Twining
Phase changes
Recrystallization

Plastic Deformation

- Plastic deformation development is accompanied by the motion of a large numbers of dislocations. The process by which plastic deformation is produced by dislocation motions is called slip. The crystallographic plane along which the dislocation line moves is called the slip plane and the direction of movement is called the slip direction. The combination of the two is termed the slip system.\(^{(1)}\)

- The motion of a single vacancy and a single dislocation emits a signal of about 0.01-0.05eV.

- The best sensitivity of modern AE devices equals 50-100eV.

(1) Materials Science and Engineering an Introduction, William D. Callister, Jr.

- Edge and screw are the two fundamental types of dislocation.

<table>
<thead>
<tr>
<th>Physical Process</th>
<th>Activation Energy (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dislocation glide</td>
<td>1.2</td>
</tr>
<tr>
<td>Formation of dislocation</td>
<td>8-10</td>
</tr>
</tbody>
</table>

- Edge, Screw, Mixed dislocation

Edge dislocation, Screw dislocation, Mixed dislocation

Edge dislocation motion
Plastic Zone at the Crack Tip

- Flaws in metals can be revealed by detection of indications of plastic deformation development around them.
- Cracks, inclusions, and other discontinuities in materials concentrate stresses.
- At the crack tip stresses can exceed yield stress level causing plastic deformation development.
- The size of a plastic zone can be evaluated using the stress intensity factor $K$, which is the measure of stress magnitude at the crack tip. The critical value of stress intensity factor, $K_{IC}$, is the material property called fracture toughness.

$$r_y = \frac{1}{2\pi} \left( \frac{K_I}{\sigma_{YS}} \right)^2$$

$r_y$ – plastic zone size in elastic material

Factors that Tend to Increase or Decrease the Amplitude of AE

<table>
<thead>
<tr>
<th>Increase</th>
<th>Decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>High strength</td>
<td>Low strength</td>
</tr>
<tr>
<td>High strain rate</td>
<td>Low strain rate</td>
</tr>
<tr>
<td>Low temperature</td>
<td>High temperature</td>
</tr>
<tr>
<td>Anisotropy</td>
<td>Isotropy</td>
</tr>
<tr>
<td>Heterogeneity</td>
<td>Homogeneity</td>
</tr>
<tr>
<td>Thick sections</td>
<td>Thin sections</td>
</tr>
<tr>
<td>Brittle failure (cleavage)</td>
<td>Ductile failure (shear)</td>
</tr>
<tr>
<td>Material containing discontinuities</td>
<td>Material without discontinuities</td>
</tr>
<tr>
<td>Martensitic phase transformations</td>
<td>Diffusion controlled phase transformations</td>
</tr>
<tr>
<td>Crack propagation</td>
<td>Plastic deformation</td>
</tr>
<tr>
<td>Cast materials</td>
<td>Wrought materials</td>
</tr>
<tr>
<td>Large grain size</td>
<td>Small grain size</td>
</tr>
<tr>
<td>Mechanically induced twinning</td>
<td>Thermally induced twinning</td>
</tr>
</tbody>
</table>

Relationship between AE and Fracture Mechanics Parameters and AE Effects
Models of AE in Metals

Plastic Deformation Model

- Plastic deformation model relates AE and the stress intensity factor \( K \).
- AE is proportional to the size of the plastic deformation zone.
- Several assumptions are made in this model: (1) The material gives the highest rate of AE when it is loaded to the yield strain. (2) The size and shape of the plastic zone ahead of the crack are determined from linear elastic fracture mechanics concepts. 

\[
\alpha = 2 \text{ or } 6 \text{ (plain stress or plain strain)}
\]

(3) Strains at the crack tip vary at \( r^{-0.5} \) where \( r \) is the radial distance from the crack tip. (4)

\[
N \propto V_p
\]

\( N \) – AE count rate

\( V_p \) – volume strained between \( \varepsilon_y \) (yield strain) and \( \varepsilon_u \) (uniform strain)

- The assumptions lead to development of the following equations for the model \( (\alpha = 2) \)

\[
V_p \approx \pi \left( r_y^2 - r_u^2 \right) B = \pi B \left[ \frac{1}{2\pi} \left( \frac{K}{E\varepsilon_y} \right)^2 \right] - \left[ \frac{1}{2\pi} \left( \frac{K}{E\varepsilon_u} \right)^2 \right] = \frac{B}{4\pi} \left[ \frac{\varepsilon_u^4 - \varepsilon_y^4}{4\pi (E\varepsilon_y \varepsilon_u)} \right] K^4
\]

\( B \) – plate thickness

\( \rightarrow V_p \propto K^4 \)

\( \Rightarrow N \propto K^4 \)
Fatigue Crack Model

Several models were developed to relate AE count rate with crack propagation rate.

\[ N' = A \Delta K^n \]  
(Eq.1) The relation between AE count rate and stress intensity factor

\[ N' - \text{AE count rate per cycle} \]
\[ \Delta K - \text{Stress intensity factor} \]
\[ A, n - \text{constants} \]

\[ \frac{da}{dN} = C \Delta K^n \]  
(Eq.2) Paris law for crack propagation in fatigue

The combined contribution of both plastic deformation and fracture mechanism is as follows for plastic yielding:

\[ N_p' = C_p \Delta K^m \frac{\Delta K^2}{(1-R)^2} \quad N_c' = C_s \frac{\Delta K^m}{(1-R)^m} \]

\[ N_p' - \text{AE count rate due to plastic deformation} \]
\[ N_c' - \text{AE count rate due to fracture} \]

\[ N' = N_p' + N_c' \]
AE Effects

- Kaiser effect is the absence of detectable AE at a fixed sensitivity level, until previously applied stress levels are exceeded.
- Dunegan corollary states that if AE is observed prior to a previous maximum load, some type of new damage has occurred. The *dunegan corollary* is used in proof testing of pressure vessels.
- Felicity effect is the presence of AE, detectable at a fixed predetermined sensitivity level at stress levels below those previously applied. The felicity effect is used in the testing of fiberglass vessels and storage tanks.

\[
\text{felicity ratio} = \frac{\text{stress at onset of AE}}{\text{previous maximum stress}}
\]
Applications
AE Inspection of Pressure Vessels
AE Inspection of Pressure Vessels
AE Testing of Pressure Vessels

100 percent hydrostatic test hold 30 min if final
98 percent 10 min hold

Pressure Policy for a New Vessel

Example of Transducers Distribution on Vessel’s Surface

Typical Results Representation of Acoustic Emission Testing

Example of Pressure Vessel Evaluation

- Historic index is a ratio of average signal strength of the last 20% or 200, whichever is less, of events to average signal strength of all events.

\[
H(t) = \frac{N}{N-K} \sum_{i=K+1}^{N} S_{0i} - \sum_{i=1}^{N} S_{0i}
\]

N – number of hits, \( S_{0i} \) – the signal strength of the \( i \)-th event, \( J \) – specific number of events

\( K=0.8J \) for \( J \leq N \leq 1000 \) and \( K=N-200 \) for \( N>1000 \)

- Severity is the average of ten events having the largest numerical value of signal strength.

\[
S_{av} = \frac{1}{10} \sum_{i=1}^{10} S_{0i}
\]

The numbers on plot correspond to sensors numbers.\(^{(1)}\)

AE Standards
AE Standards

ASME - American Society of Mechanical Engineers

- Acoustic Emission Examination of Fiber-Reinforced Plastic Vessels, Article 11, Subsection A, Section V, Boiler and Pressure Vessel Code
- Acoustic Emission Examination of Metallic Vessels During Pressure Testing, Article 12, Subsection A, Section V, Boiler and Pressure Vessel Code
- Continuous Acoustic Emission Monitoring, Article 13 Section V

ASTM - American Society for Testing and Materials

- E569-97 Standard Practice for Acoustic Emission Monitoring of Structures During Controlled Stimulation
- E749-96 Standard Practice for Acoustic Emission Monitoring During Continuous Welding
- E750-98 Standard Practice for Characterizing Acoustic Emission Instrumentation
- E976-00 Standard Guide for Determining the Reproducibility of Acoustic Emission Sensor Response
- E1067-96 Standard Practice for Acoustic Emission Examination of Fiberglass Reinforced Plastic Resin (FRP) Tanks/Vessels
- E1118-95 Standard Practice for Acoustic Emission Examination of Reinforced Thermosetting Resin Pipe (RTRP)
- E1139-97 Standard Practice for Continuous Monitoring of Acoustic Emission from Metal Pressure Boundaries
- E1316-00 Standard Terminology for Nondestructive Examinations
- E1419-00 Standard Test Method for Examination of Seamless, Gas-Filled, Pressure Vessels Using Acoustic Emission
- E1932-97 Standard Guide for Acoustic Emission Examination of Small Parts
- E1930-97 Standard Test Method for Examination of Liquid Filled Atmospheric and Low Pressure Metal Storage Tanks Using Acoustic Emission
- E2075-00 Standard Practice for Verifying the Consistency of AE-Sensor Response Using an Acrylic Rod
- E2076-00 Standard Test Method for Examination of Fiberglass Reinforced Plastic Fan Blades Using Acoustic Emission
AE Standards

ASNT - American Society for Nondestructive Testing
- CARP Recommended Practice for Acoustic Emission Testing of Pressurized Highway Tankers Made of Fiberglass reinforced with Balsa Cores.
- Recommended Practice No. SNT-TC-1A.

Association of American Railroads

Compressed Gas Association
- C-1, Methods for Acoustic Emission Requalification of Seamless Steel Compressed Gas Tubes.

European Committee for Standardization
- DIN EN 14584, Non-Destructive Testing - Acoustic Emission - Examination of Metallic Pressure Equipment during Proof Testing; Planar Location of AE Sources.

Institute of Electrical and Electronics Engineers
AE Standards

International Organization for Standardization

- ISO 12713, Non-Destructive Testing - Acoustic Emission Inspection - Primary Calibration of Transducers.
- ISO 12716, Non-Destructive Testing - Acoustic Emission Inspection - Vocabulary
- ISO/DIS 16148, gas Cylinders - Refillable Seamless Steel gas Cylinders - Acoustic Emission Examination (AEE) for Periodic Inspection.

Japanese Institute for Standardization

- JIS Z 2342, Methods for Acoustic Testing of Pressure Vessels during Pressure Tests and Classification of Test Results.

Japanese Society for Nondestructive Inspection

- NDIS 2109-91, Methods for Absolute calibration of Acoustic Emission Transducers by Reciprocity Technique.
- NDIS 2412-80, Acoustic Emission Testing of Spherical Pressure Vessels of High Tensile Strength Steel and Classification of Test Results.
More educational materials on Acoustic Emission available at www.muravin.com