Damage Analysis of Polymer Matrix Composites by Acoustic Emission Testing

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Composite materials, micro-failure analysis, delamination, fracture mechanics, impact damage, pressure gas cylinders

Abstract

This article shall illustrate which general information about damage accumulation, critical damage stages and macro-crack propagation in polymer matrix composites arise from conventional AE features and analysis of AE signals. It is referred to currently used methods for classification and identification of AE sources. Results of the theoretical analysis of inter-fiber and fiber fracture in laminates under tension are compared with monitored stress dependent AE behavior. Fracture mechanics investigation of the mode I, mode II and mixed-mode I/II delamination behavior of unidirectional, continuous fiber-reinforced laminates accompanied by AE examinations are discussed. AE results from pressure tests of damaged filament wound all-composite pressure cylinders are presented and criteria for identification of "heavy" damages are suggested. Finally, particular problems with the identification of AE source mechanisms in polymer matrix composites are pointed out.

1. Introduction

AE measurement technique is based on generation of acoustic (elastic stress or pressure) waves by fast propagating micro-failure processes or other sources. Highly sensitive piezoelectric transducers passively detect this waves by dynamic surface motion on Nanometer scale and convert it into an electric signal. The practically used frequency range is about 50 kHz … 1 MHz. Lower frequencies are often associated with extraneous noise sources or resonance effects of the transducer case. Higher frequencies are excessively attenuated by polymer matrix materials and, hence, these frequency parts of waves are carried to a distance no longer than a few centimetres from the source location.

AE testing is a real time measuring and on-line evaluation technique. It basically shall give information as to when (time, external loading parameter), how many (rate), how intense (amplitude, energy) and where (location of AE sources) stress wave emitting damage processes in specimens or structures occur. However, the interpretation of AE signals and the separation of "true" damage sources from extraneous noise or rubbing of fracture surfaces is still a major problem of this method. For a long time only conventional AE features, e.g., peak amplitude, rise time, counts, duration of the signals etc or its distributions and correlation plots were used. Recent developments in hardware components for AE monitoring and new methods of AE signal analysis yielding additional information for identification of AE source mechanisms.

2. Tools for identification and evaluation of damage stages

Currently used tools for the identification of AE sources and evaluation of damage or fracture stages of polymer composites are summarized in the following overview (see also Figure 1):

Changes in AE activity or AE intensity with time or external parameter

first AE hits/events (1)

→ onset of damage processes

characteristic changes of AE hit/event/energy rate or cumulative sum (2)

→ progressive increase – “knee point” (progressive damage and /or occurrence of new failure mechanisms)

→ continued non-decreasing or increasing AE activity and intensity during hold periods of loading (achievement of unstable damage stages)

→ increasing AE activity during unloading (rubbing of damaged areas, e.g. delaminated surfaces)

AE amplitude distribution (3)

→ number of failure mechanisms

Felicity ratio

(ratio of the load at onset of significant AE during reloading to the previously applied maximum load)

→ ultimate failure warning if it falls below a certain value (≤ 0,90…0,95)

Location of AE sources

Planar or zonal location of single events or event clusters

→ location, size, shape and growth direction of AE active zones, which are characteristic for individual forms of damage (delamination, impact, flaw)

Identification of AE sources

Tools:

- **conventional AE features** (peak amplitude, counts, duration and energy of the signal dependent on transducer, frequency filter and/or threshold; histograms and correlation plots of features)
- **waveform / wave mode analysis**
- **frequency spectrum (FFT)**
- **pattern recognition by means of neuronal networks**
- **inverse moment tensor analysis**
- **modeling of AE sources**

→ identification of AE source mechanisms

→ separation of "true" damage mechanisms from extraneous noise sources (hydraulic noise, water flow, rubbing etc)

The interpretation of AE results is also supported by FE modeling of local stress conditions and related processes of macro-failure of specimens or structures as well as by micro-mechanical modeling of microscopic failure processes (damage and fracture models).

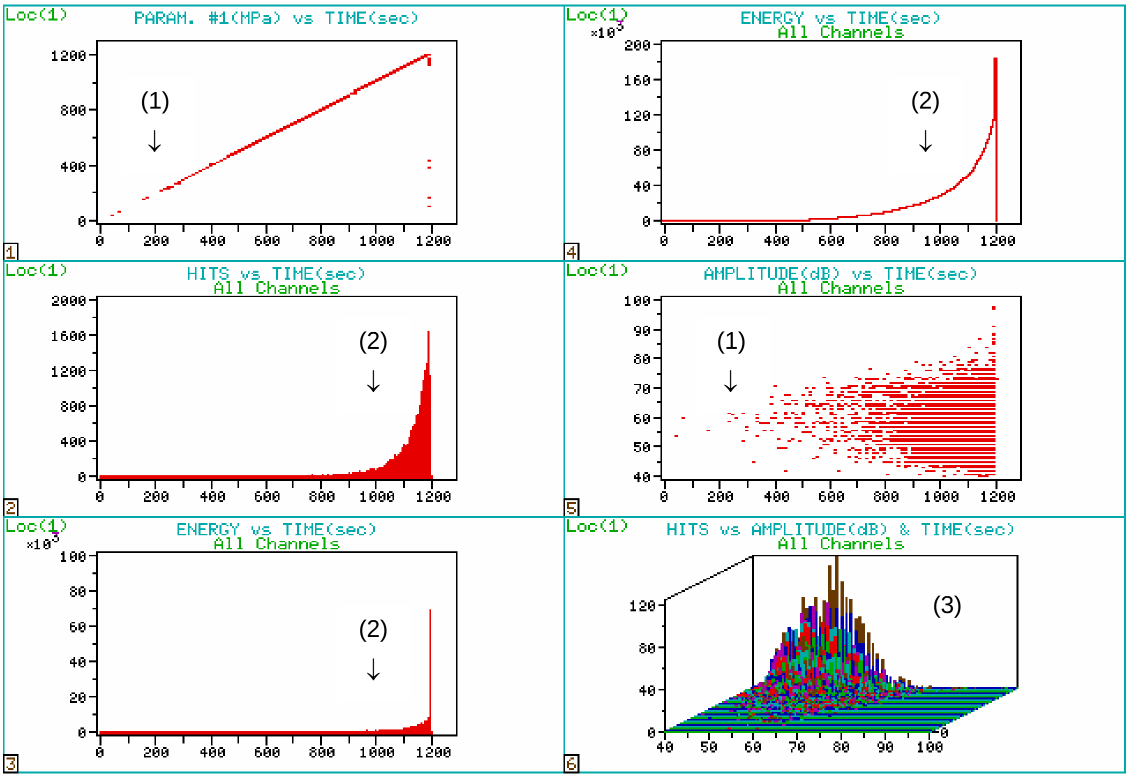

Figure 1. AE from unidirectional aramide-fiber-reinforced polyamide composite during tensile test

Active failure mechanisms in polymer matrix composites which should be detected by the AE method are

- matrix cracking
- fiber/matrix interface debonding
- fiber break
- intra- oder interlaminar crack (delamination) propagation.

A number of general approaches used for identification of AE sources are described in the literature [1, 2]. In reference [2] also specific problems and ways to the interpretation of AE signals from composite materials are discussed. From composites mostly thin-walled structures are manufactured. Therefore, mainly plate waves are generated from AE sources. Modal analysis of plate waves is based on a preferred stimulation of specific wave modes by different fracture modes, fracture geometries and location of sources (bulk or surface) and has the purpose to recognize out-of-plane (delamination mechanism) and in-plane (fiber breaks) sources. Longitudinal (extensional mode) and shear components (flexural mode) of the signals are analyzed by wavelet transform (time-frequency domain) which is suitable for AE signals whose statistical properties change with time as in the case of plate waves. The method of inverse moment tensor analysis of AE signals from volume waves of sources tries to separate shear cracks from tensile cracks during nucleation of the fracture process zone and crack propagation in larger isotropic structures.

A comparative analysis of selected international and national standards and guidelines on AE testing yields an assessment of the current status of standardization [3].

3. Analysis of micro-failure processes

For dimensioning of structures it is important to have reliable failure models. Modern physically interpretable failure criteria should be based on specified modes of failure [4, 5]. The referred criterion describes initial failure by a inter-fiber fracture mode and ultimate macro-failure by fiber fracture. Therein, inter-fiber fracture means both interfacial failure (fiber/matrix debonding) and matrix cracking. Aims of the studies were to check the fitness for use of failure models and a better interpretation of AE signals by theoretically expected modes of micro-failure. The stress for inter-fiber fracture strongly depends on fiber/matrix adhesion, matrix strength, fiber orientation and volume of fibers. Due to the problem with a reliable analytical approximation of the intra-laminar failure the database for modeling were extracted from experimental results of AE tests with load introduction transverse to the fiber orientation and with shear loading of unidirectional layers.

Figure 2 shows acoustic emission test results compared with theoretical results of a layer-by-layer stress and failure analysis of carbon-fiber/epoxy laminates by use of the inter-fiber fracture (IFF) criterion.

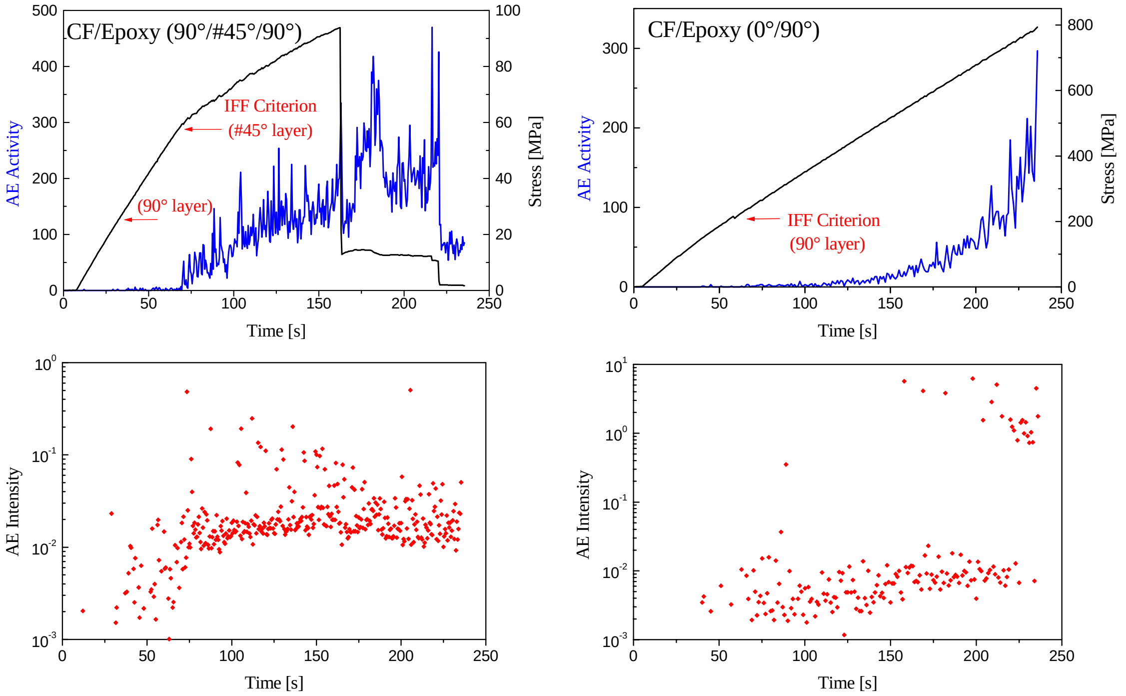

Figure 2. Initial failure analysis of two carbon-fiber/epoxy laminates by means of IFF modeling (arrows) and acoustic emission behavior

At theoretical approximated loading levels for initiation of inter-fiber fracture AE signals are really detected. Different failure processes are indicated by its individual AE characteristic (here dimension of AE activity means hits/s and AE intensity is given by mVs/hit):

- Laminate $(90°)_6$ / $(\pm 45°)_3$ / $(90°)_6$: transverse failure of fiber/matrix interfaces and matrix in 90° laminated layers are of low AE activity and AE intensity whereas shear failure of matrix and interfaces in ±45° woven layers superposed by delamination processes between 90° und ±45° layers are of medium AE intensity but high AE activity; pure shear deformation in ±45° layers produce very high AE activity after ultimate fracture of 90° layers at the stress maximum.

- Woven fabrics (0°/90°): transverse failure of fiber/matrix interfaces and matrix; breaks of fiber bundles in 0° direction is associated with very high AE intensity at stresses higher approximately 70% of the laminate strength.

From this a energy criterion for separation of inter-fiber and fiber failures in specimens can be derived by means of conventional AE features. Breaks of fiber bundles are detected by AE signals with ten to hundredfold higher energy rates.

4. Studies of delamination behavior

Several standardized fracture mechanics tests are used for the purpose to determine the resistance against inter-laminar crack propagation. The delamination behavior of unidirectional fiber-reinforced polymer laminates made from glass-fibers or carbon-fibers with thermoplastic or epoxy matrix were studied using different fracture tests such as Double Cantilever Beam test (mode I), End Notched Flexure test (mode II) und Mixed Mode Bending test (mixed mode I/II) [6, 7].

The application of AE examination has two aims. On the one hand this technique shall contribute to a more objective determination of initiation loads (for micro-crack initiation and onset of macroscopic delamination) and give additional information on micro-processes which appear during delamination for a better micro-mechanical understanding of the toughness behavior. On the other hand experiments exemplify one of the most frequent macroscopic failure processes in composite structures.
An example is given in Figure 3. It shows the AE behavior of an unidirectional reinforced glass-fiber/polypropylene composite during mode I delamination.

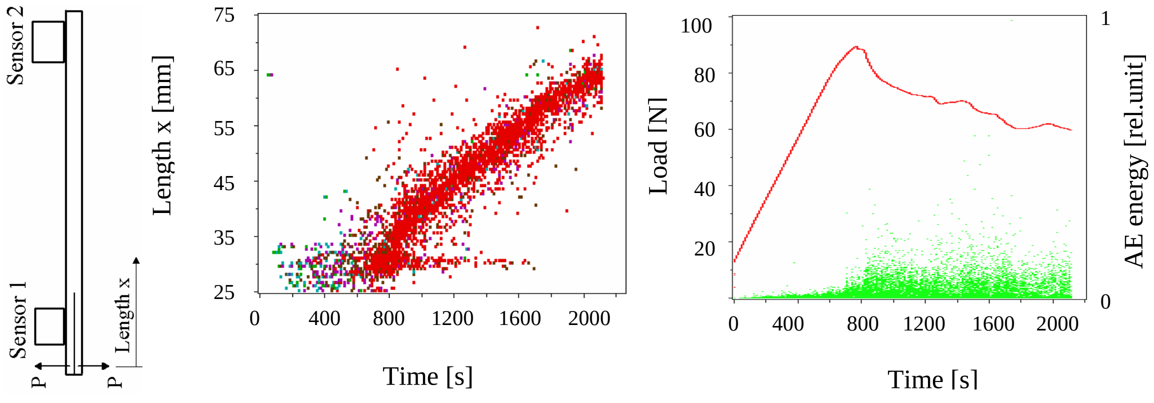

Figure 3. Fixed AE transducer position for location of AE sources in delamination tests (chart left). Time-dependent position and size of the damage zone determined by location of AE events with amplitudes at the transducer ≥ 60 dB_{AE} (plot middle) as well as delamination load (line) and AE signal energy (points) from DCB (mode I) tests on unidirectional reinforced glass-fiber/polypropylene (plot right).

For the first objective following statements has resulted:

- Location of AE sources around the delamination tip enable the determination of
  → position of the delamination front
  → initiation points (loads):

  $\text{INIT}_{\text{locAE}}$: micro-crack initiation at the delamination tip
  $\text{INI-PROP}_{\text{locAE}}$: onset of macroscopic delamination propagation
  → delamination speed
  → size and shape of energy-dissipative zones around the delamination tip (with the assistance of FE modeling).

- A correlation between AE energy and mechanically released energy during stable delamination propagation exists.
- Number and intensity of AE signals are dependent on matrix and fiber material as well as fiber/matrix adhesion.
- Breaks of bridging fibers between the opened delamination surfaces frequently occur in composites with weak interface adhesion and result in AE sources behind the delamination tip.
- Instable fracture stages with fiber breaks in the bended cantilevers yield to AE signals with high peak amplitudes and high energies at the delamination tip.

With reference to detectability and size assessment of propagating delamination areas in composite structures it can be concluded that mode I delamination generate most and strongest AE sources (maximal AE peak amplitudes detected few centimeter from the source are 90...100 dB_{AE}, but maximal amplitudes from shear fracture mode II are only 70...80 dB_{AE}) associated with the largest process zone around the delamination tip compared with other fracture modes. Consequently, the detectability of propagating delamination tips should be good. At this most of the AE sources are emitted from areas behind the delamination tip.

5. AE inspection of pressure cylinders

In order to investigate its AE characteristic of damages in all-composite cylinders (made of a plastic liner and fully-wrapped with a filament wound carbon-fiber/epoxy shell) the cylinders were externally damaged by impacts or flaws and were pressurized up to the allowed test pressure. After a varying number of internal pressure cycles the cylinders were inspected performing pressure tests accompanied by AE testing. For the purpose of comparison a non-damaged cylinder whose micro-damages only result from pressure cycling was also inspected. At the fist pressurization after damage a dramatic rise of AE activity is detected compared with a pressure test before the damaging. A subsequent pressure cycling up to the working pressure should simulate refuels and lead to a local stress reduction due to a further degradation by micro-damaging in the region of macro-damages. Caused by local stress relief following periodic AE tests after predetermined pressure cycles show a decrease of AE activities and AE intensities with increasing number of cycles.

For example, Figure 4 shows AE results from a pressure test of an impact damaged cylinder (impact with $W_{\text{kin.}} = 2 \times 70$ J in the central part of an oil-filled cylinder) after 5000 pressure cycles ($\Delta p = 5 – 300$ bar) up to a test pressure of 360 bar.

From our test results it can be concluded that impact and critical flaw damages are clearly detectable also after longer service intervals. AE peak amplitudes of maximal 90...100 dB_{AE} at the source location were calculated by means of a distance amplitude correction procedure. This is in agreement with peak amplitudes which appears during delamination tests at specimens.

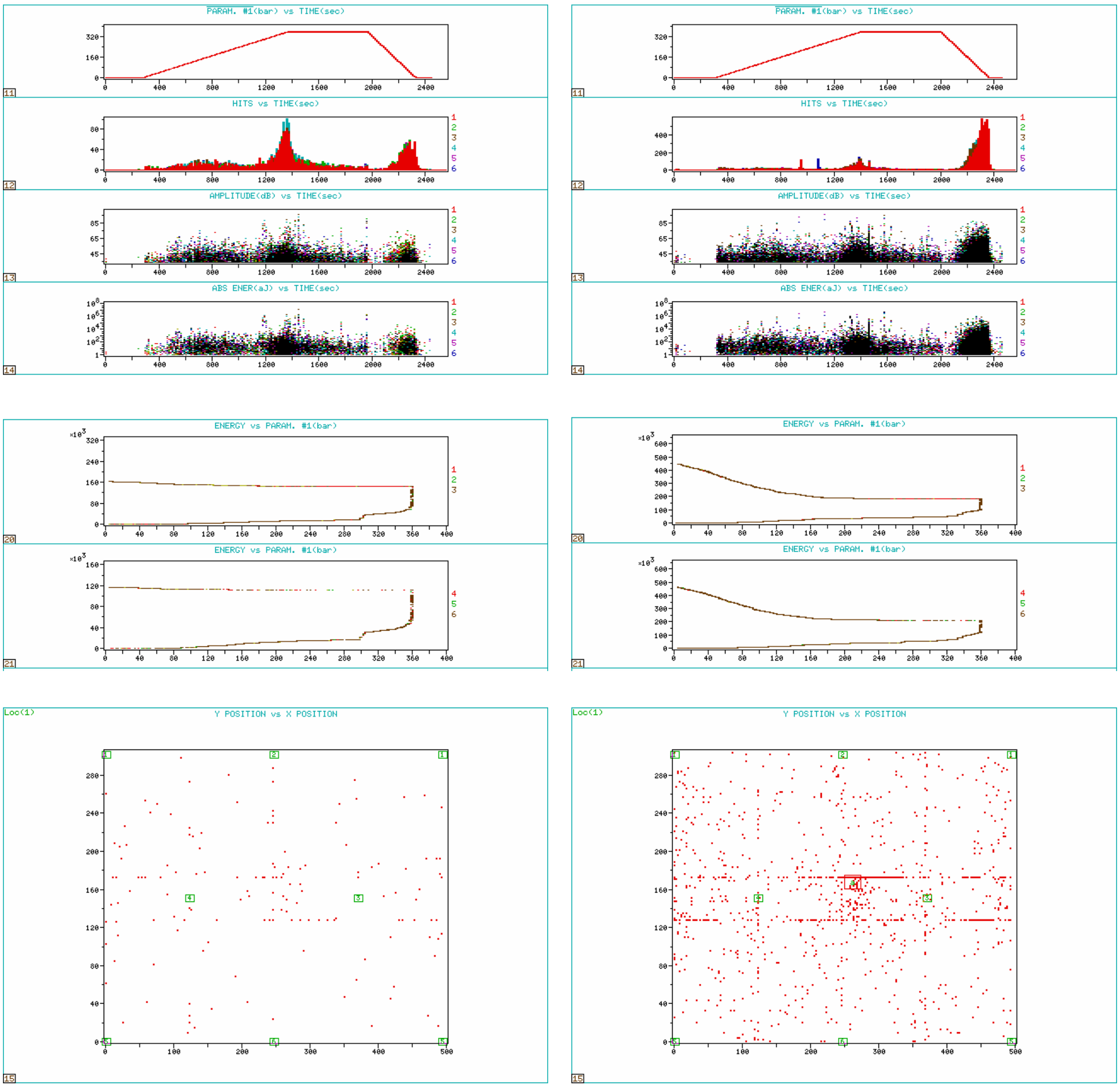

Figure 4. AE testing of MCS 6,8litre/300bar all-composite cylinder without external damage (left) and with impact damage (right) after 5000 cycles

top: test pressure, AE hit rate, peak amplitude and energy of AE signals vs. time

middle: energy sum of hits detected by different transducer groups vs. test pressure

bottom: planar located AE sources; cluster size: range / 20 [5%] and minimum Level: E > 10.000

Following possible qualitative criteria for identification of “heavy” damages in filament wound pressure cylinders using AE features from periodic inspections with only one pressure ramp are suggested:

- much higher hit sums cumulated over the complete pressure test
- AE transducers which are located near damaged regions
    - record more hits of higher energy (energy sum of planar located sources or derived from zonal location)
    - detect higher hit sums during depressurization compared with those of the previous increase of the pressure ramp
    - show a progressive increase of AE energy during depressurization (sources from rubbing of damaged zones!?)
- formation of clusters of AE sources with much higher energy release than from surrounding area (if a planar location is successful applicable).

However, a distinction of AE source mechanisms from loading and unloading stages based on conventional AE features was not achieved.

6. Identification of AE source mechanisms

The advantage of fibre composites compared with other materials is the generation of very strong stress waves associated with fiber breaks and delamination processes.

In previous papers [8, 9] we suggested a method to distinguish matrix cracking and fiber break sources by a power spectrum analysis of the monitored AE waveforms. It was assumed that matrix cracks have at least 70 % of the signal power in the 100 to 350 kHz and fiber break in the 350 to 700 kHz frequency interval.

Technical structures from composite materials have plate-like geometries and, hence, effects of wave propagation such as geometrically determined attenuation, wave type interactions, reflections, wave mode conversions at free surfaces etc cause a clearly marked change of the wave in time and frequency domain on its path from the source location to the transducer position. In addition composites with a viscoelastic polymer matrix possess a comparatively high material attenuation which is dependent on frequency, temperature and wave modes especially for frequencies greater than about 400 kHz.

Figure 5 demonstrates the strong difference in the waveforms and frequency spectra with a different transducer spacing to one and the same source.

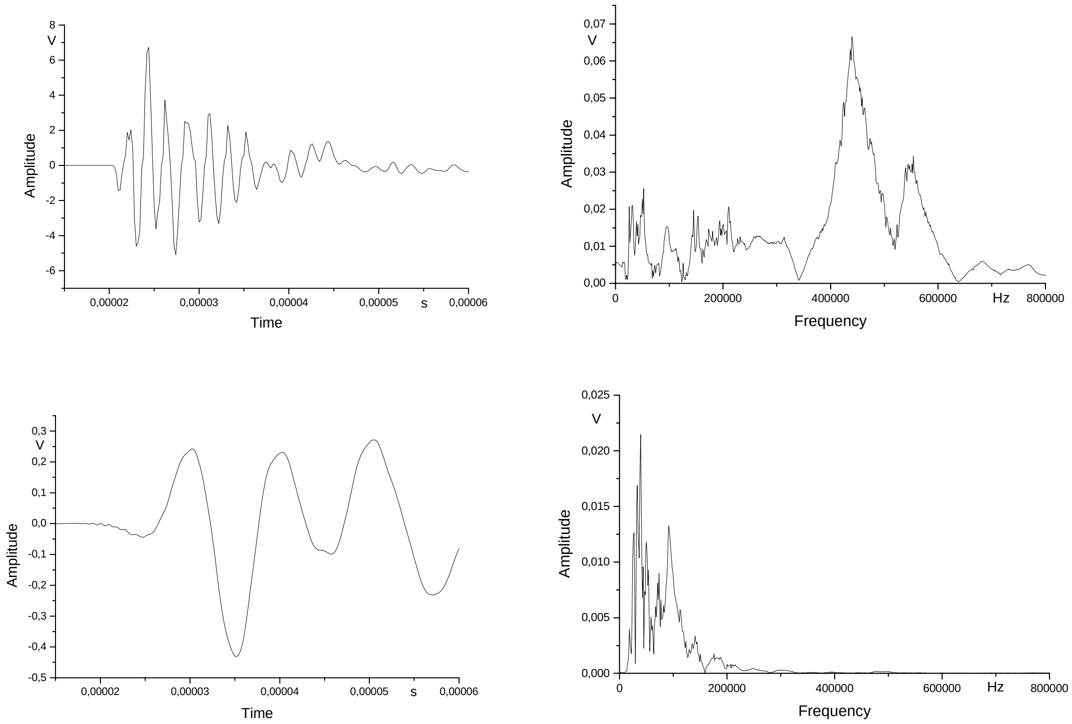

Figure 5. Distance dependent waveforms and power spectra of AE signals from single-fiber fragmentation (fiber diameter 80 µm) in epoxy matrix (recorded with transducers of operating frequency range 200-750 kHz, amplifier with filter HP 20 kHz, sampling 5 MHz) at a distance of 7 mm (top) and 43 mm (bottom; only the first counts of the waveform are shown) from the source

These results show that we must strongly restrict our above mentioned method of identification of AE source mechanisms from its power spectra to a very short distance of a few millimeter from the source. Additionally to geometrical and materials influences, modulations of waveforms and spectra by the strong frequency dependent sensitivity of AE transducers and electronic frequency filters must be accounted for. All these effects cause spectra of AE signals which have no similarity with theoretically assumed AE sources (Figure 6).

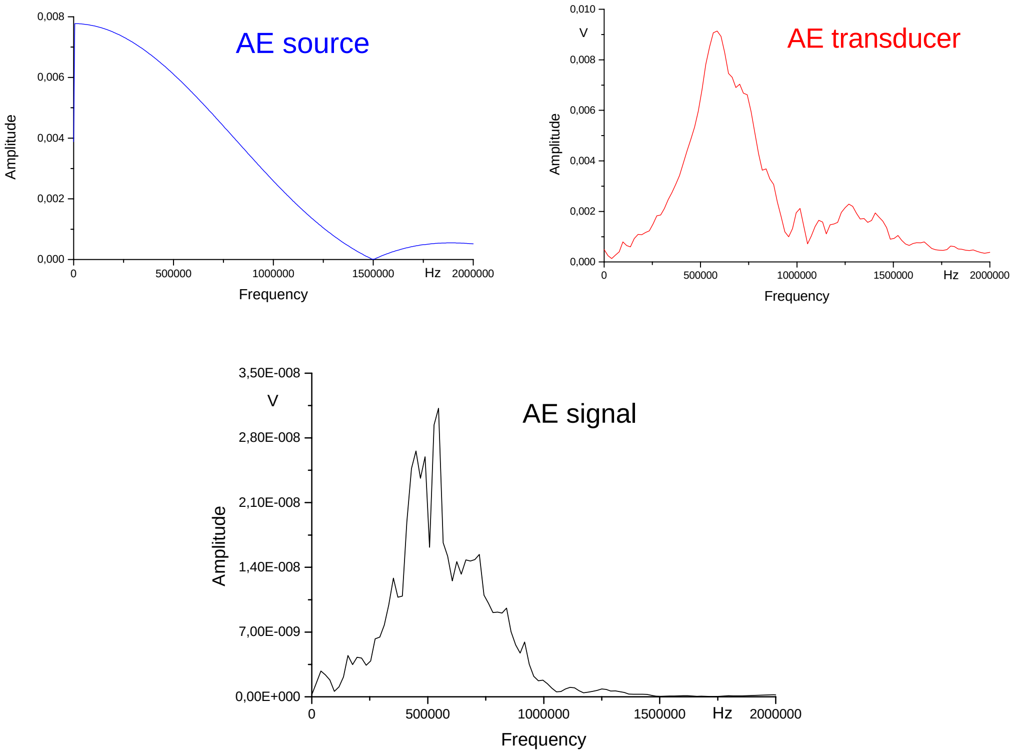

Figure 6. Calculated spectrum of AE signal from the product of transfer functions of the source, propagation medium, transducer and electronic system for waveform recording in the frequency domain

The main influence in the frequency domain comes from the more or less resonant behavior of AE piezo-transducer.
That means for polymer matrix composites there is practically no chance of source identification from frequency spectra of AE signals. An alternative method for separation of different modes of fracture seems to be the modal analysis of plate waves. Hence, all above mentioned effects also influence the result of this approach.

7. Conclusions

- AE testing is a powerful method for online detection and analysis of matrix, fiber and interface related active fracture processes in composite materials.
- A number of tools for identification and evaluation of damage stages and failure mechanisms exists. They are based on changes in AE activity or intensity features, location of AE sources as well as the analysis of waveforms, spectra and wave modes from AE signals.
- Stress waves emitted by fiber breaks cause much higher AE amplitudes than other mechanisms.
- Propagating delamination also produce strong AE sources from areas near the delamination tip.

- At pressure tests “heavy” damages in structures, as impacts or flaws are detectable by formation of cluster of located high-energy AE sources and a significant higher AE activity and intensity, especially during depressurization periods.
- From studies of transfer functions of components of the measuring chain it must be concluded that it is difficult to separate micro-failure mechanisms in polymer matrix composites from frequency spectra of AE signals. The source information is mainly distorted by the high attenuation of polymer materials related to high-frequency parts of stress waves and the transfer function of the AE piezo-transducer.
- Due to all discussed problems it is deduced that an identification of AE sources from the recorded waveforms of AE signals seems to be possible only by means of a numerical modeling of AE sources as well as wave propagation in time and place. For this purpose source function, wave-guiding medium, geometry of the examined structure and characteristic of used AE transducer must be clearly defined.

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