Damage Analysis of Fiber Reinforced Composites using Acoustic Emission

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Abstract

This paper discusses damage analysis of fiber reinforced composites using acoustic emission. Acoustic emission is physical phenomenon at which arises release of energy due to the stimulation by external or internal stress. This method ranks among the non-destructive material testing methods. For analysis purposes, composite material with carbon fibers was used, from which test specimens were made for loading in uniaxial tension. The loading was subsequently monitored by acoustic emission. Selected parameters measured by acoustic emission were evaluated in their dependence on the type of damage occurred in the material during the loading process. The evaluation of damage was performed using light, stereo and scanning electron microscopy.

Keywords: composite, fiber, matrix, acoustic emission, fracture, damage

1. Introduction

The presence of flaw or defect in the microstructure of composite material may have negative impact on overall operability of the construction or part. The operational activities (fatigue, impact or static overload) can results to formation of degradation processes in the structure of composite material. Properties of the material are reduced which can lead to a sudden collapse and failure of the part. For this reason it is necessary to study the degradation processes, materials behavior under the load during the operation and potential occurrence of damage or failure of the part. [1-3]

This work deals with the analysis of damage processes in the microstructure of the carbon fiber reinforced composite material. It is the first step for further investigation of behavior of composite under the load together with influence of stress concentrator and enviromental influences such as humidity and temperature.

1.1. Composites

Composite materials are gaining more and more importance in various industries. The higher applicability has been developed primarily as result of requirement to reduce the weight while maintaining or improving the materials properties of construction or parts. Other properties of composite materials contribute immensely to their increasing use in the industrial applications often to the detriment of other materials. Outside the lower weight, composites have also good corrosion resistance, fatigue resistance, gradual crack propagation, damping properties and notch impact strength. [4]

For construction applications, the most used composite materials are fiber reinforced. It is due to the better properties in comparison to particle reinforcement. Nowadays the largest usage of fiber composites is in aerospace, automotive, cosmic and energy industry. The most often used type of composite in mentioned industries is based on carbon fibers. In airliners, application often exceeds 50% and primary usage is for supporting elements and shells. In sports aircraft, the composite usage is the highest due to requirements on properties of construction, mainly on toughness and strength. [5] Also automotive industry is faced with the need to reduce weight which leads primarily to reduction in fuel consumption. The usage of carbon fibers also helps to improve the dynamic properties of hybrid and electric cars and increase the overall life of components. The components for wind power plants – rotor blades are made of carbon fiber reinforced composite. For construction parts of space shuttle, such as nose portion or the wing leading edge the carbon fibers are used in form of RCC (Reinforced Carbon Carbon). [4-5]

There is continuous progress in replacement of conventionally used materials by composites due to good combination of advantages of strength properties and weight reduction. [4]

1.2. Acoustic emission

Acoustic emission is a nondestructive method (NDT) used for materials testing. The biggest applicability of acoustic emission is in the field of constructions. Its ability to detect and localize the presence and activities of defects can be used for prevention of occurrence of serviceability limit state of construction during the operational activity and it is possible to ensure its safe operation. [7-9]

Using the acoustic emission method, it is possible to detect the elastic waves spreading through the material. Mechanical or thermal load generates the waves from the present flaws and defects in the structure of the material. Waves are detected on the surface with sensors in the form of electric signal i.e. acoustic emission signal. Generated wave record is evaluated by usage of its parame-

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ters (counts, events, amplitude, rise time...). [8, 10-11] If more than one sensor is used, the source location of signal can be evaluated due to difference in time of arrival of wave to each sensor. Linear localization with two sensors of acoustic emission is used for parts where longitudinal dimensions are bigger than transversed. For other types of components with different shape (pressure vessels) more than two sensors have to be used. [7-9]

The biggest disadvantage of acoustic emission is its inability to detect the static or inactive types of defects. Effectiveness and efficiency depends mainly on the type of material, construction of tested object, load history and environmental influences. In terms of composite materials acoustic emission is complex phenomenon which may leads to incorrect identification of source, if not enough attention is paid to attenuation of propagating waves and external noise. Due to these negative influences it is possible to mistaken the disruptive effect (e.g. vibration) for the damage spreading in the material. [7-9]

2. Experiment

The base material was made of a high performance tough amin cured epoxy matrix HexPly 8552 and carbon fibers AS4 12K which is primary used in aerospace structures. Laminate was cured in an autoclave according the manufacturer schedule. Then two types (181 and 361) of tensile specimens with different thickness and plies orientation were manufactured according to ASTM standards. [12] Subsequently the composite tabs were added on the edges of the specimens. Basic information such as dimensions and parameters of testing specimens are given in Fig. 2 and in Tab. 1. Manufactured specimens were scanned for possible present defects or flaws using automatic Ultrasonic Flaw Detector OLYMPUS EPOCH 1000 (C-scan). Ultrasonic C-scan maps for each testing specimens are given in Fig. 1.

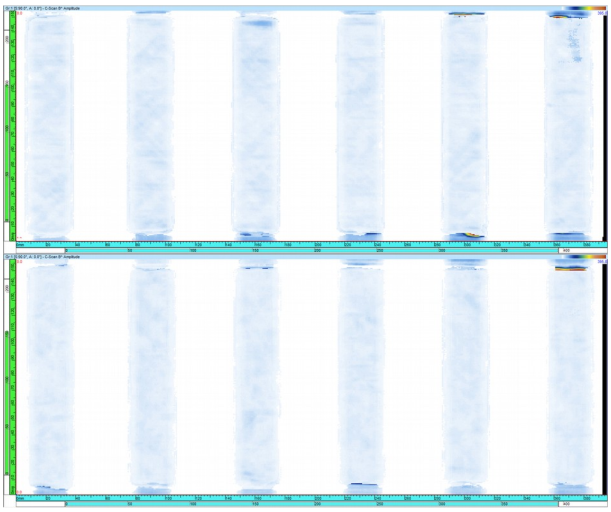


Fig. 1. *C-scan mapping of tensile testing specimens*

Universal measuring and diagnostic acoustic emission system DAKEL was used for measurement. Four IDK-09 sensors (PZT class 200) together with DAKEL preamplifiers were used for detection and signal was preamplified with a preamplifiers level of 35 dB. The sensors position fixation (15 mm from each tab) was done using superglue. Before testing, acquisition parameters were calibrated according to Hsu-Nielsen source test [8]. This test consist of breaking a pencil of 0.5 mm diameter on the specimens surface. One breakage of pencil generates acoustic emission signal similar to natural AE source and sensors detects these signals as a strong burst. From this test values of acoustic wavespeed were determined for each side of testing specimen.

Table 1. *Parameters of tensile testing specimens (X = 1-3)*

Type	Label	t [mm]	Layup	Plies	Quantity
181	181-N-X	2.976	$(0°)_2$ $(+45)_8$ $(-45°)_6$ $(90°)_2$	16	3
361	361-N-X	6.324	$(0°)_{10}$ $(+45)_{10}$ $(-45°)_{10}$ $(90°)_4$	34	3

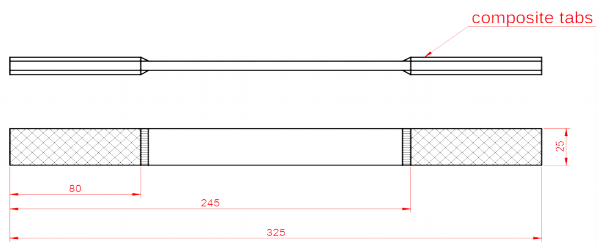


Fig. 2. *Geometry and dimensions (in mm) of testing specimens*

Instron 55R1185 was used as an universal testing machine for tensile test. Test method was done according to standard [12] with crossheads speed of 0.5 mm/min at temperature 23 °C and 41.3 % R.H. From the test, basic properties were obtained: tensile strength, Poissons no. and modulus of elasticity. E modulus was determined using an extensometer and by a linear regression as a least square fit of a linear function between the strain values of 0.1 and 0.3%.

After the tensile test the fracture surface analysis was done using the Nikon SMZ1500 stereomicroscope, optical microscope Neophot 32 and scanning electron microscope JEOL JMS 7600F. Evaluated damage types were compared with acoustic emission parameters.

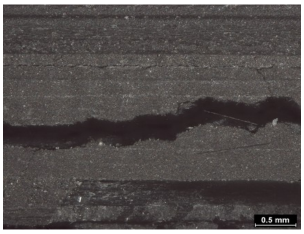
3. Results and discussion

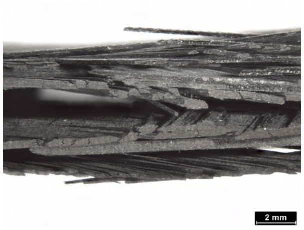
3.1. Tensile test

At first failure modes from tensile test was evaluated according to ASTM standard [12]. The specimens mode of failure was multimoded (angled, lateral and edge delamination) for both types where for 181 type was M(A,D)WT and M(A,D)GM while for 361 specimens was M(A,L,D)WT and M(A,L,D)GM modes. The final tensile strength is 418 MPa for 181 specimen and 736 MPa for specimen 361. Resultant modulus of elasticity is 34.9 GPa for specimen 181 and 53.7 GPa for specimen 361. Poissons no. is similar for both 0.471 and 0.457 for 181 and 361 respectively.

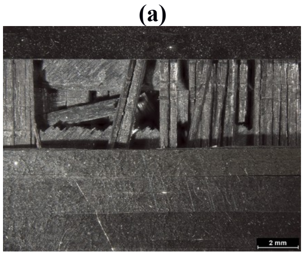
3.2. Fracture analysis

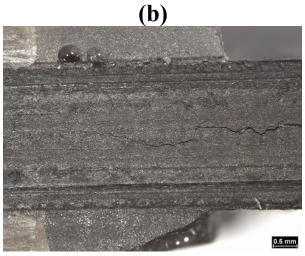
Using the stereo-microscopy, basic types of damage was determined. Damage of sides and surface of tensile specimens 181 and 361 is shown in Figs. 3-4. Large degree of delamination was observed on both sides of specimens (see Fig. 3a-3b and Fig. 4a). Delamination cracks spread through the specimen towards the edges followed by a local matrix cracking (see Fig. 3d and Fig. 4c). Massive ply splitting was detected at specimen 181 around the area of fracture (see Fig. 3b-3c). At specimen 361, ply splitting spreads often along the ±45° oriented plies (see Fig. 4d) which is similar pattern as for specimen 181 (see Fig. 3b).





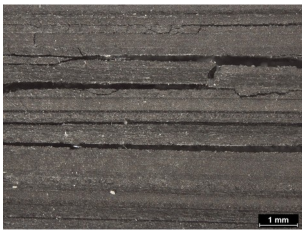
(a) **(b)**

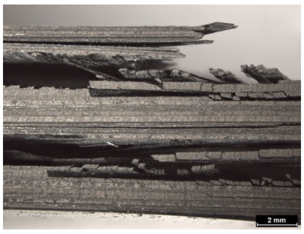




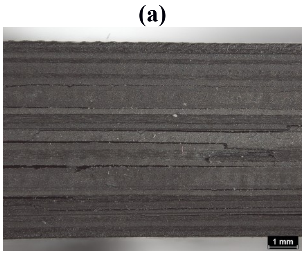
(c) **(d)**

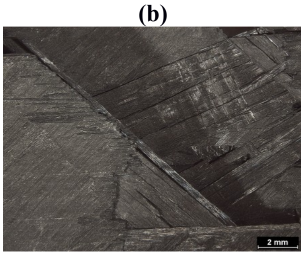
Fig. 3. *Fracture analysis of specimens 181 using stereomicroscopy*





(a) **(b)**



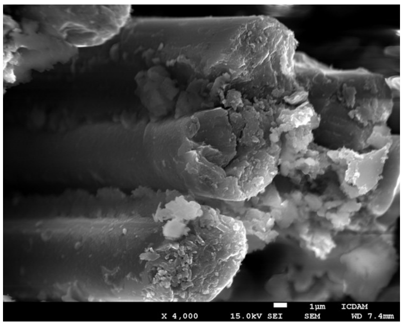


(c) **(d)**

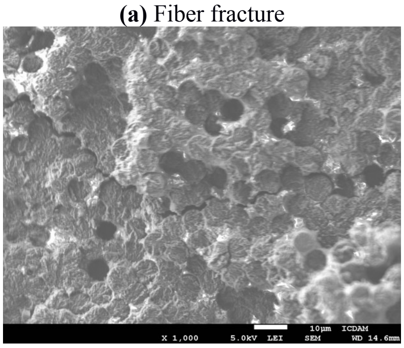
Fig. 4. *Fracture analysis of specimens 361using stereomicroscopy*

For more detailed analysis the scanning electron microscopy had to be used. Several damage types have been observed. The most common type is the translaminar failure mechanism – fiber fracture, fiber cracking (see Fig. 5a), fiber pullout and intralaminar cracks in the matrix (see Fig. 5b). In Fig. 5a and Fig. 6a the fracture surface of the fibers can be seen. These two figures represents the high and low energy regions respectively. In case of low energy, the fracture surface is smooth with characteristic radial crack growth direction lines and the fiber arrangement is uniform in comparison to high energy area. This corresponds to findings in [13].

The fibers have good adhesion towards the epoxy matrix. It can be seen in Fig. 5a that fibers are encapsulated in epoxy resin. Another confirmation are traces of fiber pullout but in a small scale in Fig. 5b.

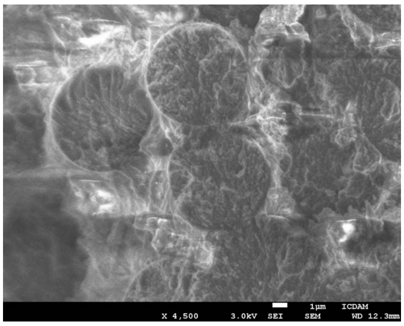


(a) Fiber fracture

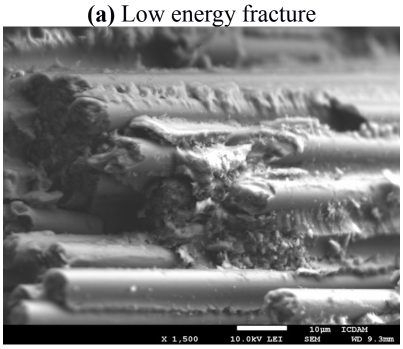


(b) Matrix cracking and fiber pullout

Fig. 5. *Fracture surface analysis of specimens 181 using scanning electron microscopy*



(a) Low energy fracture



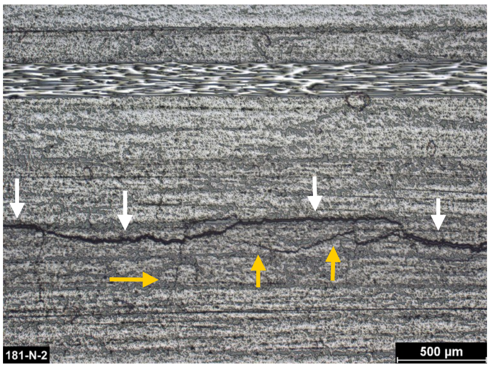
(b) High energy fracture

Fig. 6. *Fracture surface analysis of specimens 361 using scanning electron microscopy*

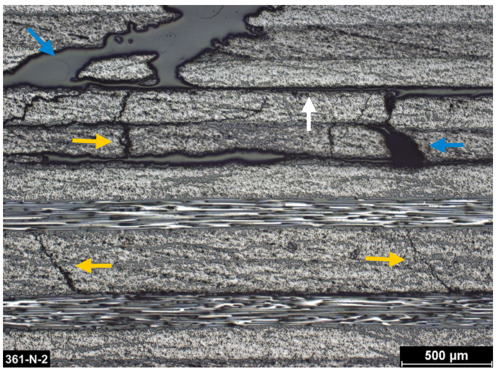
3.3. Metallographic evaluation

The images from light microscopy show formation of several damage types in the microstructure. The presence of delamination is found between the layers (white arrows in Fig. 7a and Fig. 7b). Delaminations are often connected to each other by secondary and lateral interlaminar cracks (under 45° and 90°) in the matrix (orange arrows). Connection of delamination damage can be clearly seen at specimen 361 in Fig. 7b together with transition of matrix cracking to creation of large voids which can initiate the ply splitting mechanism (blue arrows in Fig. 7b). The crack propagation along the fiber/matrix interface and connection may easily lead to the massive damage or failure of the composite material.

The resin rich areas might help to initiation of damage in the composite structure because of no side fiber support when the load is applied. No major porosity from the manufacture process have been found in the microstructure, which corresponds to results of performed C-scan (see Fig. 1). The observed damage types also corresponds to [13-14].



(a) Delamination and secondary cracks



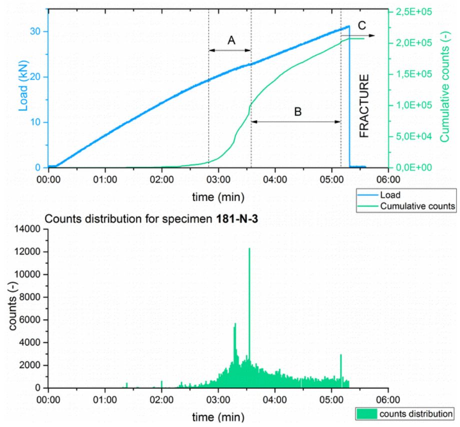
(b) Delamination and ply splitting

Fig. 7. *Metallographic evaluation of specimen 181 and 361*

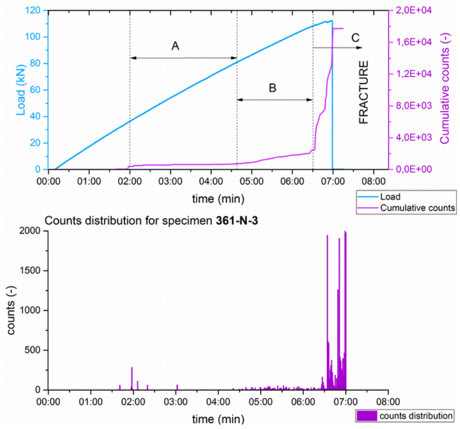
3.4. Evaluation of acoustic emission

In Fig. 8 the correlation of tensile test data with acoustic emission parameter – counts can be seen. Pairing the tensile test diagram with cumulative value creates several areas in the diagrams. In the diagram for 361 in Fig. 8b, there is not much activity in the area A which is probably due to the extensometer removal from the specimen shortly after the measurement. In the B area, the number of counts are increasing and at the begging of C area, the values goes sharply up. According to activity at the bottom, in the B area, there is a formation of damage type of low energy such as matrix cracking (see Fig. 7a and 7b) while at the C area, another kind of damage occur but of higher energy i.e. fiber cracking and fiber pulling.

The diagram for 181 (see Fig. 8a) specimen is different, which corresponds to the the fact, that it has different number of plies in comparison to 361. Highest activity of counts is at the borders of A and B areas. It can be said, that there is a formation of some complex type of damage such as ply splitting.



(a)

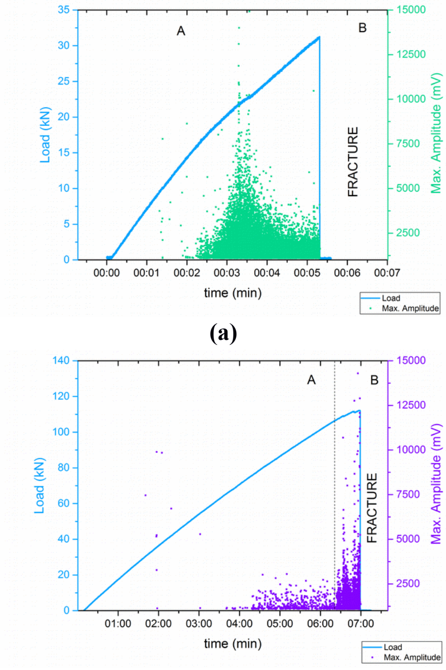


(b)

Fig. 8. *Correlation of acoustic emission parameters with tensile test data*

The results for second correlation with amplitude can be seen in Fig. 9a-b. Amplitude correlations are very similar to correlation of counts. The highest activity of amplitude parameter according to distribution is at the border of A and B area and towards the fracture area, the activity is decreasing (see Fig. 9a). The one explanation for this behavior is the earlier occurrence of delamination and ply splitting, due to lower number of plies and thus lower strength.

In area A (see Fig. 9b), there are a few amplitude signals which is again due to extensometer removal during the tensile test. However in the B area, the activity of amplitude is rising. The small values of amplitude in the area A can be assigned to low energy damage process such as matrix cracking while the high values in the B area are processes with higher energy like fiber pullouts or fiber cracks followed by delamination processes.



(a) (b)

Fig. 9. Correlation of acoustic emission parameters with tensile test data

At this state the results serve as confirmation, that acoustic emission can be used for analysis of fracture behavior of this type of composites. For more detailed analysis further investigation is needed. Additional parameters have to be added (events) together with other types of evaluation (localization or frequency analysis).

4. Conclusion

- The uni-axial tensile test was done for 2 types of testing specimens and the basic mechanical properties were evaluated.
- The types of damage – matrix cracks, delamination, ply splitting, fiber fracture and fiber pullout were determined using stereo light and scanning electron microscopy.
- Correlation between the acoustic emission parameters (counts, amplitude) and tensile test data have been done.
- Behavior of some parameters of AE was assigned to a certain kind of damage types.
- Further investigation of correlation of acoustic emission parameters and damage in the microstructure will be done together with effect of additional environmental influences.

Acknowledgments

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