# FRACTOGRAPHY AND DAMAGE ANALYSIS OF CARBON/EPOXY COMPOSITES UNDER STATIC AND DYNAMIC LOADS AT ELEVATED TEMPERATURES

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**Abstract:** This paper presents the microstructural and fractographic analysis of damage in carbon/epoxy composites after static and fatigue strength (shear) tests at elevated temperature. The microstructural tests and fractographic analysis confirmed the complexity of degradation process and degradation mechanisms in composite structure. Multiple cracks, delaminations and interface degradation between fibre and matrix have been observed. The fracture analysis indicate the occurrence of characteristic failure area: matrix river lines, matrix rollers, fractures and reinforcing fibres imprints. The interface, except of the type of components and their features, is the principal factor determining the properties of composite material. The quality of the bonding between the reinforcing phase and matrix, mechanism of composite cracking as a whole as well as cracks of individual components are directly affected by the interface.

**Key words:** Carbon Fibre Reinforced Polymer, Microstructure, Damage, Fractography, Shear, Mechanical Tests

## 1. INTRODUCTION

Nowadays, the fibre reinforced polymeric composites belong to the materials groups used in technical applications with the highest development potential in the years to come owing to favourable combination of their properties e.g. high strength and rigidity versus low density, fatigue characteristics and chemical resistance. Therefore these materials are widely used mainly in the aircraft and automotive industries as well as in sporting goods sector (Morgan, 2005; Chung, 1994).

At the moment, the carbon fibre reinforced composites are particularly interesting part of the wide group of composite materials. High strength properties, fault tolerance (impact resistance), dimensional stability and high fatigue strength are required in case of carbon composites (Chung, 1994; Freeman, 1993).

Therefore the damage mechanisms in carbon composites are an important aspect to be considered in the designing and manufacturing process as well as in the service life of composite structures. The degradation processes in composite materials are more complex than in case of metal materials. The damages of reinforcing fibres and matrix, delaminations as well as degradation of fibre/matrix interface are observed (Gamstedt et al., 2009; Wu et al., 2010)

Particularly important are the static and fatigue strength tests under the influence of shear stress and the determining role of matrix which may lead to significant reduction of strength properties of composite materials (Hodgkinson, 2000).

In many cases, the optimization of composite materials is possible as a compromise between the achievement of high mechanical properties and high shear strength of composites (Hodgkinson, 2000).

Furthermore accelerated degradation of mechanical properties in composites is possible in case of an intensive impact of environment conditions i.e. humidity and increased temperatures. Therefore the evaluation of damage mechanisms may become more complex (Jen et al., 2008).

The damage process in composite materials can be associated with structure designing phase, applied materials and manufacturing technology or elements operation. Valuable information about damage processes is obtained from fractographic tests, particularly about the reasons leading to damages of individual components, damage - cracking initiation, errors in manufacturing process or defects in materials. The fractographic tests make it possible to understand more deeply the damage process and its interpretation contributing to further development, among others in the scope of damage criteria (Greenhalgh, 2009).

The evaluation of damage character is the essential question in the carbon fibre reinforced composites (as state of art engineering materials) often exposed to the influence of increased temperatures and shear stresses (in static and dynamic processes).

In the present study, the authors described microstructural and fractographic analysis of damage in carbon/ epoxy composites after the static and fatigue tests (shear test, configuration [±45]) at increased temperatures.

## 2. MATERIAL AND METHODS

The carbon/ epoxy composites made of unidirectional prepreg tape in HexPly system (Hexcel, USA) in configuration $[\pm45]_8$. Epoxy resin has been used as composite matrix and carbon fibres have been applied as high strength reinforcing. Nominal percentage (v/v) of reinforcing fibres in composite was equal to about 60%. The composite materials have been produced using autoclave technique in the Material Engineering Department in Lublin University of Technology.

The fractographic analysis has been performed on the materials after the following tests:

- static shear strength (temp. +85ºC);

– fatigue shear strength (temp. +50 ºC *tension-tension* method);
– specimen after the highest number of cycles.

The tests for strength and fatigue properties have been performed in accordance with relevant standards applicable to this type of materials (ISO, ASTM).

The microstructural and fractographic analysis has been carried out using the optical microscopic equipment (Nikon MA200, Japan) and Scanning Electron Microscope (SEM) (Zeiss Ultra, Germany).

## 3. RESULTS AND DISCUSSION

Fig. 1 illustrates the macroscopic image of carbon/epoxy composites after (static and fatigue) shear test. In both cases, the damage occurred in the central part of the material in the form of complete damage of reinforcing fibres and matrix as well as delamination in interlayer planes.


**Fig. 1.** Specimens of carbon/ epoxy composites after shear test: a) static test; b) fatigue test

The microstructure of carbon/ epoxy composite after the static shear test is illustrated in Fig. 2a.

The delaminations between successive layers and lateral cracks connected to each other are visible along fibre/matrix boundaries.

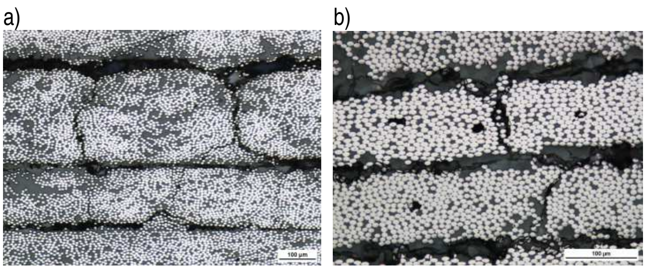



**Fig. 2.** The microstructure of carbon/epoxy composite after the shear tests: a) static test; b) fatigue test (cross- section)

In case of carbon/epoxy composite after the fatigue shear test (Fig. 2b), the presence of delaminations is found between layers and lateral cracks across the composite layers. Multiple porosities have been observed, particularly within interlayer spaces. Individual cracks combine with porosities forming the grid of cracks.

The process of porosities forming in carbon/epoxy laminate occurred probably in course of manufacturing i.e. polymerization process (loss of vacuum bag tightness). Occurred porosities may affect not only the quality of composite structure but also may lead to the reduction of strength and fatigue properties of the material.

The mechanism of crack propagation process along the fibre/matrix boundaries with visible degradation of interface has been illustrated in Fig. 3. Multiple areas of initiation and cracks are visible (loss of adhesion) and may combine together easily leading to the damage of composite.

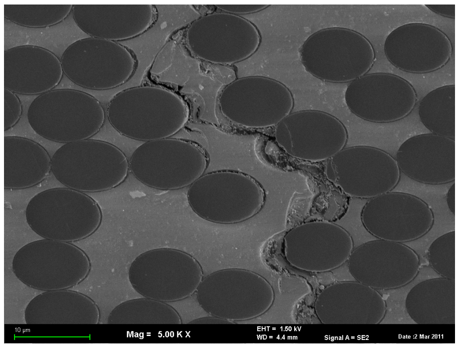



**Fig. 3.** Cracks and degradation of fibre/matrix interface (cross- section); SEM

The fractography of fractures is applied as one of principal methods as well as interpretation of the results obtained in strength and fatigue tests.

Essential data on composites behaviour relating to the fractographic analysis of damage in composite structures are contained in the studies elaborated by Clements and Purslow (Greenhalgh, 2009). Owing to the differences occurring in composites damage morphology, two damage regions have been indicated by Clements i.e. high energy region and low energy region. Fig. 4 illustrates the fracture surface obtained in performed tests.

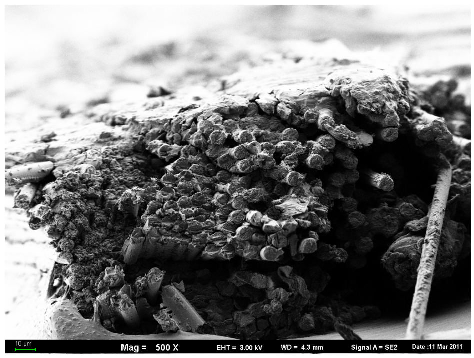
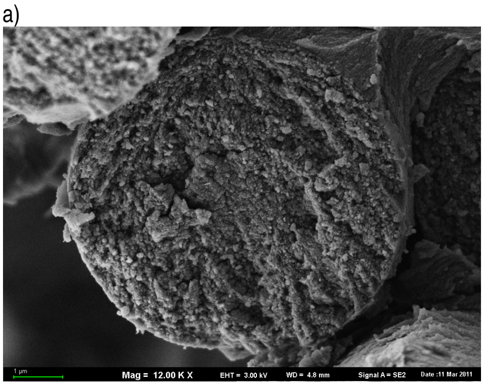



**Fig. 4.** Fracture surface in examined composites after static and fatigue tests. Damage region is typical for high energies; SEM

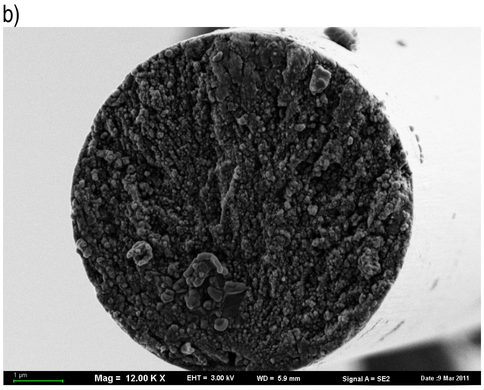
In case of low energies, the surface on fibres fracture is smooth and the fibres are arranged in an uniform manner. Their location on the same level is the symptom of low energy level occurring at the time of structure damage. However in case of the damage characterized by the high energy level and observed also in materials under analysis, the surface of fracture is non-uniform and the reinforcing fibres are located on various levels (Greenhalgh, 2009).

No significant differences appeared from the analysis of damage fractures after static and dynamic tests. Fig. 5 illustrates the fractures of reinforcing fibres.

a)



b)



**Rys. 5.** Fractures of carbon fibres after shear strength tests: a) static test; b) fatigue test

A characteristic crack initiation zone (source) has been observed in both cases. Radially propagating crack growth direction lines are the symptoms of brittle cracking phenomenon occurred in fibres in course of structure damage. This phenomenon has been confirmed by observations of Greenhalgh (2009).

The surface of matrix after performed static shear tests has been illustrated in Fig. 6.

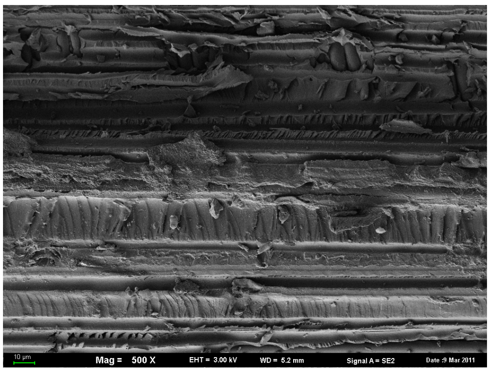


**Fig. 6.** Surface of matrix fracture after performed static shear tests; SEM

The figure illustrates visible characteristic matrix flow lateral lines indicating the structure damage growth direction lines which are situated between adjacent fibres or their imprints.

Fig. 7 illustrates a characteristic morphology of matrix rolling and the creation of resin "flakes" inclined to surface. This effect is characteristic for damage as a result of fatigue processes with high number of cycles and under the impact of shear forces. The dimension and distribution depends on the space between the matrix and fibre. The number of cycles and the strength of fibre/matrix bonding are the factors affecting such behaviour of the matrix material. Under fatigue loads, the matrix plasticity is increased and its deformation takes place (Fig. 7). The damages are initiated locally in the matrix. There the micro-damages propagate along fibre/matrix boundary in the initial phase and grow until the interface degradation is achieved and the fibre – matrix bonding is lost (Greenhalgh, 2009).

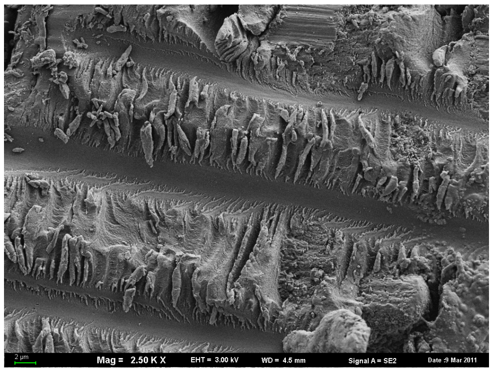


**Fig. 7.** Morphology of matrix fracture surface in carbon/ epoxy composite after fatigue shear strength test; SEM

In both cases, characteristic imprints of reinforcing fibres have been observed on damage surface (Fig. 8); the fibres have been completely separated from the matrix (Greenhalgh, 2009).

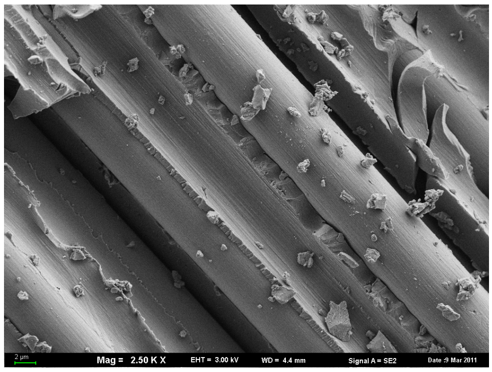


**Fig. 8.** Characteristic imprints of reinforcing fibres on damage surface; SEM

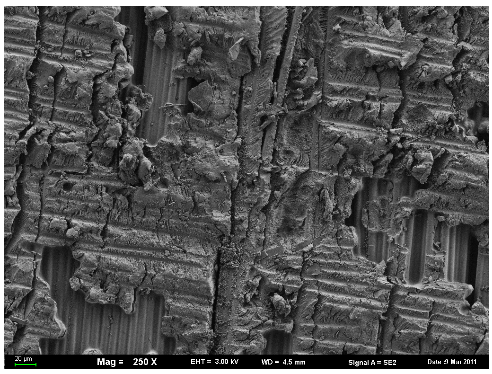


**Fig. 9.** Surface of carbon/ epoxy composite fracture with visible fracture layer and fibres after performed fatigue shear tests

Fig. 9 illustrates the surface of matrix material after fatigue shear strength tests with visible traces of arrangement of individual fibres. There are multiple cracks and deep furrows in matrix, parallel to each other, oriented in the direction perpendicular to the previous direction of fibres (Greenhalgh, 2009).

The analysis of fractures, surfaces of fibres and composites subjected to cyclic loads makes it possible to determine the type of damage, with consideration of components bonding; the analysis depends on the type of fibres, their arrangement, type of matrix, bonding between phases and the type of applied load (Hartwig et al., 1998).

The damage mechanism in polymeric composites subjected to diversified loads significantly differs from conventional materials. The growth of cracks, degradation of fibres and matrix as a result of the impact of high stresses lead to the complete damage of material (Tai et al., 1995). The damage of fibres as a result of the impact of low stresses can be caused by the loss of bonding on fibre/matrix interface and degradation of reinforcing fibres is possible before the complete damage of composite (Tai et al., 1995).

Cracks growth in polymeric composites reinforced with unidirectional fibres arranged in ±45 direction may depend on the occurrence of structural discontinuities (porosities) and micro-damages of high values of shear stresses occurring between the layers (Putic S. et al., 2003).

## 4. SUMMARY

The microstructural tests and fractographic analysis for composites with epoxy matrix reinforced with carbon fibres demonstrated the complexity of degradation process and its mechanisms in composite structure. The presence of multiple cracks (laterally oriented) and delaminations has been observed in composites microstructure in both cases (in static and dynamic conditions).

Any significant differences in fractures morphology (brittle cracks of reinforcing fibres) have been not demonstrated in course of fractographic analysis of individual reinforcing fibres. Some characteristic zones have been found on the fractures surface, among others matrix river lines (static tests), matrix rolling (fatigue tests), cracks and imprints of reinforcing fibres. The character of fractures surface is associated with high damage energies.

The damage process in composite materials is associated mainly with fibre/matrix interface and with the properties of matrix material. Multiple degradation areas have been observed on fibre/matrix boundary: initiation sources, loss of adhesion, cracks propagating along fibre / matrix boundaries.

In summary it can be concluded that the interface except of the type of components and their features, is the principal factor determining the properties of composite material. The quality of the bonding between the reinforcing phase and matrix, mechanism of composite cracking as whole as well as cracks of individual components are directly affected by the interface.

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The tests performed in the framework of the Project No POIG.0101.02-00-015/08 in Innovative Economy Operational Programme (PO IG). The Project co-financed by the European Union from the European Fund for Regional Development.