THE INFLUENCE OF LOADING METHOD OF ORTHOTROPIC COMPOSITE ON FATIGUE STRENGTH

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ABSTRACT

The bending fracture mechanisms and interfacial behaviour of unidirectional composites were investigated in console-bending (***u***=const; ***P***=const; ***R***=0; ***R***=-1) with simultaneous acoustic emission monitoring. Microfractures occurring at fiber breakages and matrix damage were examined by AE parameters and observations by scannig microscope. As a result, it was faund that many AE events were monitored in the bending speciments. A fractographic analysis permits to define dominating damage mechanisms for various types of fatigue load. Using AE parameter especially energy (MARSE) failure modes can be identified.

KEYWORDS

Composite materials, fatigue, acoustic emission, damage mechanisms.

INTRODUCTION

In recent years, the burgeoning technology of composite materials has opened new horizons to scientists and engineers. The use of these materials is rapidly expanding, especially in high performance structures such as aircraft and other vehicles. In such applications fatigue loading is a dominant factor, therefore a good recognition of fatigue strength and life is necessary obviously, it can accelerate the utilisation of fiber reinforced composite materials, if the ability of predicting fatigue strength and fatigue failure life is improved increasingly. This can be achieved either through extensive and costly experimental work or by using reliable prediction models such as fatigue failure criterion, which can reduce the experimental work.
The state of damage in composite materials subjected to external load contains multiple and local failure in a form of matrix cracks and splitting delaminations, broken fibres, interface failures, e.t.c. Detailed discussions of the failure processes in composite during tension – tension fatigue loading are given in [1]. Fracture behaviour and acoustic emission in bending tests on single fiber composites during static load have been presented in [2]. More recently, the acoustic emission techniques have been considered as a promising non destructive testing procedure, which can provide information about failure mode, damage progression and damage criticality in real – time [3]. Monitoring acoustic emission during fatigue loading appears to offer a particular procedure for detecting fatigue damage and damage growth.

INVESTIGATION STANDS AND METHODICS OF FATIGUE TESTS RUNNING

The investigations of a composite fatigue strength have been made according to a console scheme of loading on independently designed and made stands [4] with referred to zero (***R*** =0) and symmetrical (***R*** =-1) loading cycle, with frequency 1–7 Hz. The loading process was controlled by a given displacement (***u*** =const), or a given force (***P*** =const). The value of $2\cdot 10^6$ cycles has been considered as a limit value.
The material fatigue strength has been presented by a *S_N* diagrams (Fig. 1) [5]. The specificity of conducted investigations was, that during the cyclic loading of a test piece – full loss of strength (load capacity) was not been achieved. The decrease of loading parameter for 40% in relation to its value at the beginning of fatigue process, has been treated as a conventional moment of a test piece failure. According to this assumption, a failure criterion can be expressed as follows:

with displacement control: $$P_k / P_0 = 0.6 \qquad (1)$$

with force control: $$u_0 / u_k = 0.6 \qquad (2)$$

where: $\boldsymbol{P}_o$, $\boldsymbol{u}_o$, $\boldsymbol{P}_k$, $\boldsymbol{u}_k$ – are the values of force, bending moment, tension, or displacement adequately in the beginning and final stadium of a fatigue process.
Test pieces, designed for testing, were made of glass fibre (of continuous type) and epoxy resin, in a form of a beam of width 10 mm and 3.1 mm. Glass fibre (E= 70 GPa) of diameter 10 μm is placed in parallel to a flat bar axis. Weigh contents of glass fibre in a composite is – 80%.
During fatigue loading of the investigated test pieces, the acoustic emission (EA) signals were registered. MISTRAS-2001 processor has been applied for AE investigations . It enables to register acoustic signals, generated by a test piece material; during its loading. Energy parameter (MARSE) [3, 5] was mainly used there.
After the investigations were over, according to criteria (1), (2) – the investigated test pieces were observed through a scanning microscope JMS-5400. The pictures of adequate cross-sections are presented and analysed below.

FATIGUE STRENGTH OF ORTHOTROPIC COMPOSITE

The results of tests concerning the peculiarity of a composite behaviour during its fatigue have been described in particular in previous studies [5, 6]. It has been shown, that in a fatigue process, according to a considered criterion (1) or (2), a loading parameter (***P*** force, or displacement ***u***) changes for approx 40 %. Moreover increase of flexibility ***C*** for approx 40% is observed there. In Fig. 1 there are presented the dependences *S_N* (σ_{Lo}_*N*) obtained witch displacement control (***u*** =const.) for the referred to zero (***R*** =0) and symmetrical (***R* =-1)** loading cycle and with force control (***P*** =const) with ***R*** =0. In the comments presented close to adequate diagrams – there are also equations which describe the curves and correlation coefficients.
The presented diagrams prove, that the greatest resistance of investigated material to fatigue is with the referred to zero (***R*** =0) loading cycle, with displacement control of loading process (***u*** =const.). The change of loading method onto ***P*** =const causes lowering of *S_N* curve. The fatigue life of being investigated material - lowers more, with change of load from asymmetrical (***R*** =0) to symmetrical (***R* = -1**).

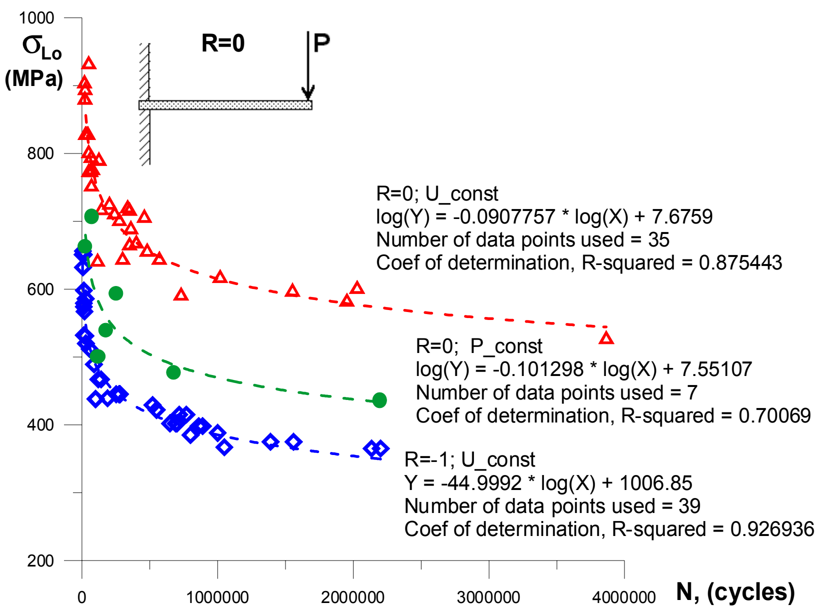

Fig. 1. Fatigue life ***S_N*** curves obtained with various asymmetry of a cycle and various loading methods.

The presented location of fatigue curves is connected with some distinctness in mechanisms of material failure, what was mentioned by authors in previous studies [6, 7]. Investigations of test pieces, fatigued according to criterion (1) or (2), conducted with scanning microscope confirm that assumption. Figures 2, 3, 4 show a number of pictures which characterise the orthotropic composite fatigue process peculiarities. Pictures have been taken from these test pieces, which correspond -for each fatigue curve - to relatively high level of loading and low period of life (< 5%), and inversely: to relative low loading and high period of life (> 85%).
The analysis of pictures presented in Fig. 2 enables to find the differences in failure mechanisms for the test pieces fatigued with relatively high loads, thus enabling to realise the criterion (1) or (2) in a period up to 5% in relation to an assumed base life ($2 \cdot 10^6$). The most damaged material is with a symmetrical fatigue cycle (***R*** =-1, ***u*** =const) (Fig. 2.3). The picture of the side part of a test piece (Fig. 2.3a) shows the big number of delaminations and cross cracks, what is also confirmed by cross-section view (Fig. 2.3b). Cracks are symmetrically laid on a whole cross-section of a test piece. With a test piece loaded with referred to zero cycle, (***R*** =0, ***u*** =const.), on its side surface we find delaminations and separate cross- cracks (Fig. 2.1a). The number of delaminations for ***R*** =0 is a little greater than with symmetrical cycle (***R*** =-1). Absolutely lower number of cross-cracks occurs there (compare Fig. 2.1 and Fig. 2.3). With relatively low loadings, enabling to realise the criterion (1) or (2) for 85-100% of a base life, of test pieces with ***u*** =const, pictures show that damages and displacement of fatigue dependences *S_N* (Fig. 1) are compatible.
On pictures presented in Fig. 2.2 and Fig. 3.2, which correspond to composite fatigue with ***P*** =const, ***R*** =0, we observe the lower level of damages. But *S_N* fatigue curve for such loading type is between the curves for ***u*** =const, ***R*** =-1, and ***u*** =const, ***R*** =0, not as it could be expected from the pictures analysis.
The lowest location of a curve ***u*** =const, ***R*** =-1 can be justified by presence of compressing stresses, which mainly cause damage of glass fibres. With relatively high level of loading stress σ_{Lo} =632 MPa we observe the delaminations of a material along the glass fibres and their breaking;- what proves the operation of three failure mechanisms: delamination, decohesion and cracking of fibres (Fig. 2.3). While with σ_{Lo} =367 MPa (Fig. 3.3) we find very little number of cracks in cross section – what proves a very low level of delamination

and decohesion. But we observe big roughness of side surface (Fig. 3.3a) what proves a great number of cracked glass fibres (Fig. 4.3 a).
Curve *S_N* obtained with ***u*** =const, ***R*** =0 is on the highest level. The analysis of pictures shows, that with high load σ_{Lo} =751 MPa mechanisms which cause delamination namely delamination and decohesion have bee realized, what is proved by great number of cracks (Fig. 2.1, Fig. 4.1). While relatively smooth side surfaces of a test piece prove small share of breaking mechanism of fibres in a composite failure (Fig. 2.1, Fig. 4.1). With stress level σ_{Lo}=581 MPa (when 100% of assumed durability is realised) (Fig. 3.1) we observe slight delamination and increase of side surface roughness, what shows cracks of glass fibres. But surface roughness is much smaller, than in a case of test piece loaded with symmetrical cycle (compare Fig. 3.1 and 3.3).
Concerning the test pieces fatigued with ***P*** =const and ***R*** =0 there are the least delaminations, while relatively a lot of cracked glass fibres (Fig. 2.2, Fig. 3.3, Fig. 4.2). For such type of load, the roughness (which corresponds to fibres cracking) is smaller, than with load ***u***=const, ***R*** =-1 and greater than with ***u***=const, ***R*** = 0, what causes the location of a fatigue curve as it is shown in Fig. 1.
On the ground of the above observations we can assume, that the level of a composite fatigued resistance depends on the possibility of realisation of adequate failure mechanism in it. The most dangerous is such type of loading, which causes the cracking of glass fibres.

THE ANALYSIS OF FATIGUE PROCESS WITH USE OF AE SIGNALS

To identify the mechanisms of composite failure during the fatigue investigations, the registration of acoustic emission has been conducted. The basic signal for analysis purposes was an energy parameter, which comprehensively includes such signals of acoustic emission, as amplitude and event durability (Fig. 5). The conducted tests enabled to settle some relations between the registered acoustic signals and observed mechanisms of a composite failure. It has been confirmed, that signals of low (to 60-40 v·s) and medium (800–280 v·s) energetic level correspond with material delamination process (delamination and de-cohesion). While breaking of glass fibres – we register the high-energy level (from 300-500 to 25000 v·s) signals [5, 7].
From an example diagram of energy (E) signal change while test piece fatigue, loaded with ***u*** =const, ***R*** =0 and σ_{Lo} = 751 MPa, presented in Fig. 6 - we can confirm, that very high–energetic impulses of signals correspond with decrease of a test piece rigidity. We can assume, that these events correspond with cracking of these glass fibres, which previously were separated in a delamination (delamination and decohesion) process of a resin matrix.
The process of matrix delamination in the beginning period of fatigue (to 8000 s) dominates and signals of low level mainly correspond to it. The second half of fatigue period of an analysed sample shows the domination of high-energetic signals, what characterises the process of glass fibres cracking.

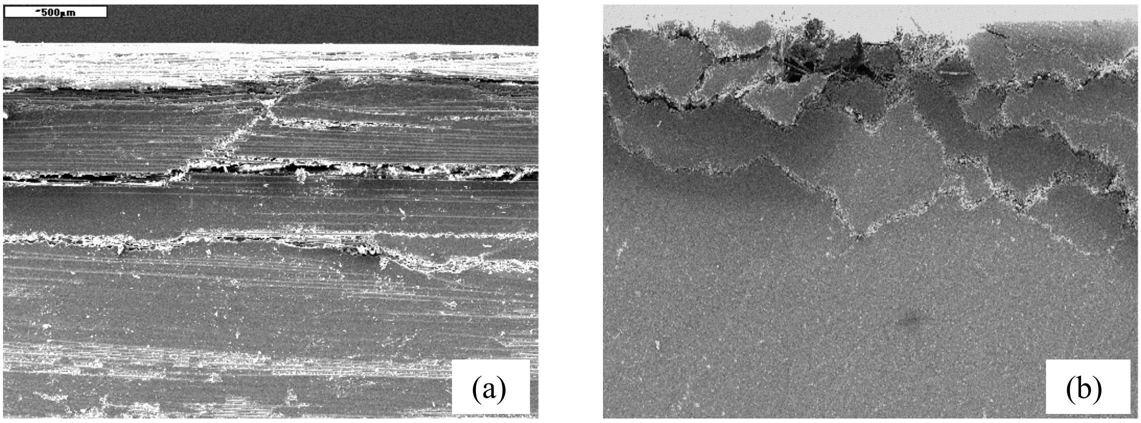

Fig. 2.1. The specimen after fatigue load (***u*** =const, ***R*** =0) σ_{L0} = 751 MPa; σ_{Lk} = 450 MPa; ***N*** =69000; (a) –side surface (x50); (b)- cross-section (x35).

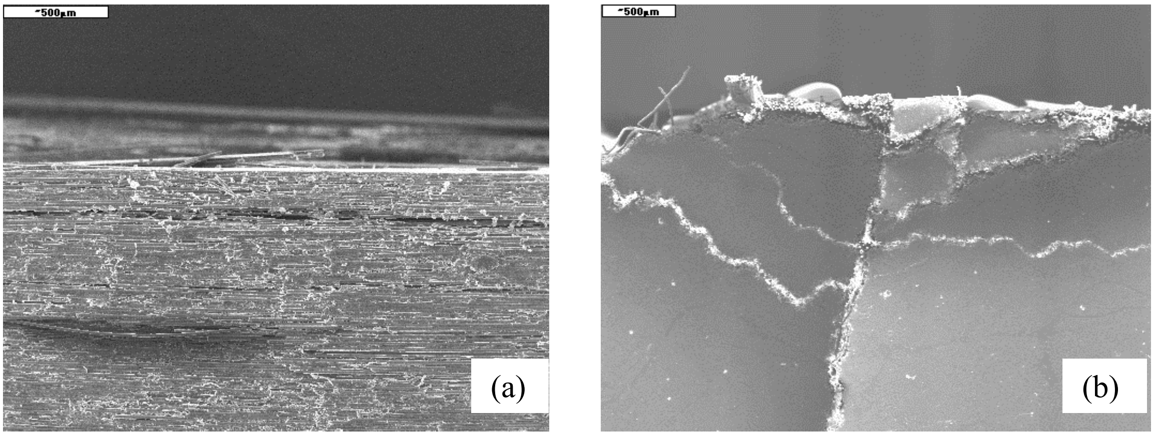

Fig. 2.2. The specimen after fatigue load (***P*** =const, ***R*** =0) σ_{L0} = 700 MPa; ***N*** =73000; (a) –side surface (x50); (b)- cross-section (x35).

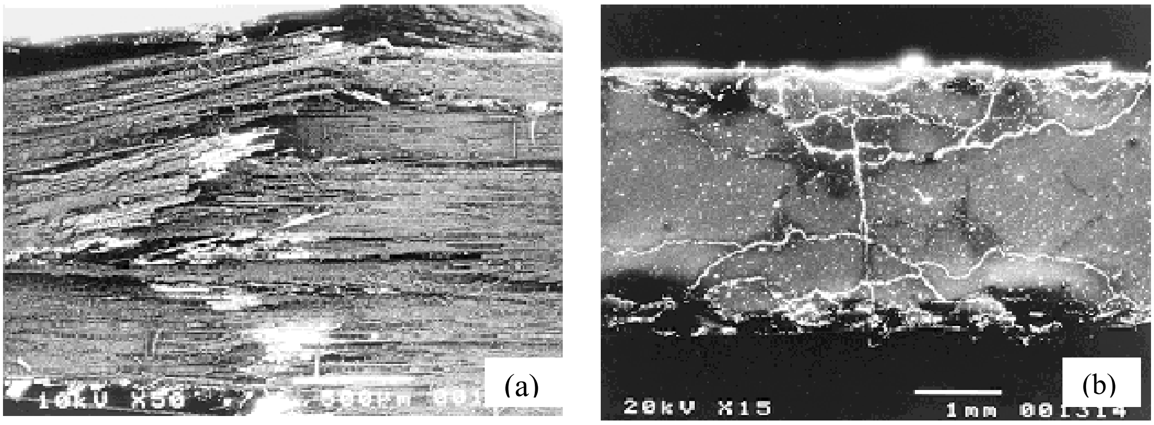

Fig. 2.3. The specimen after fatigue load (***u*** =const, ***R*** =-1) σ_{L0} = 632 MPa; σ_{Lk} = 450 MPa; ***N*** =70000; (a) - side surface (x50); (b)- cross-section (x15).

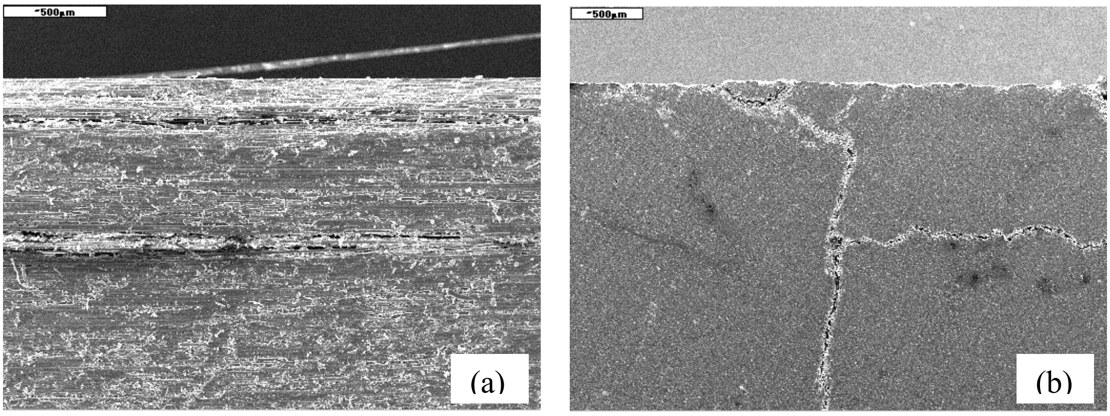

Fig. 3.1. The specimen after fatigue load $\boldsymbol{\sigma_{L0}}$ = 581 MPa (***u*** =const, ***R*** =0); $\boldsymbol{\sigma_{Lk}}$ = 402 MPa; ***N*** =2000000; (a) - side surface (x50); (b)- cross-section (x35).

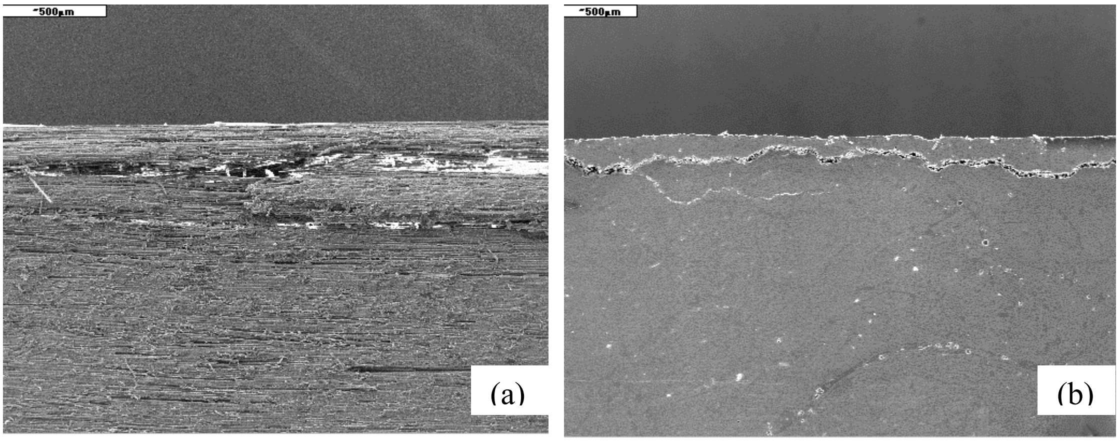

Fig. 3.2. The specimen after fatigue load (***P*** =const, ***R*** =0) $\boldsymbol{\sigma_{L0}}$ = 490 MPa; ***N*** =350000; (a) - side surface (x50); (b)- cross-section (x35).

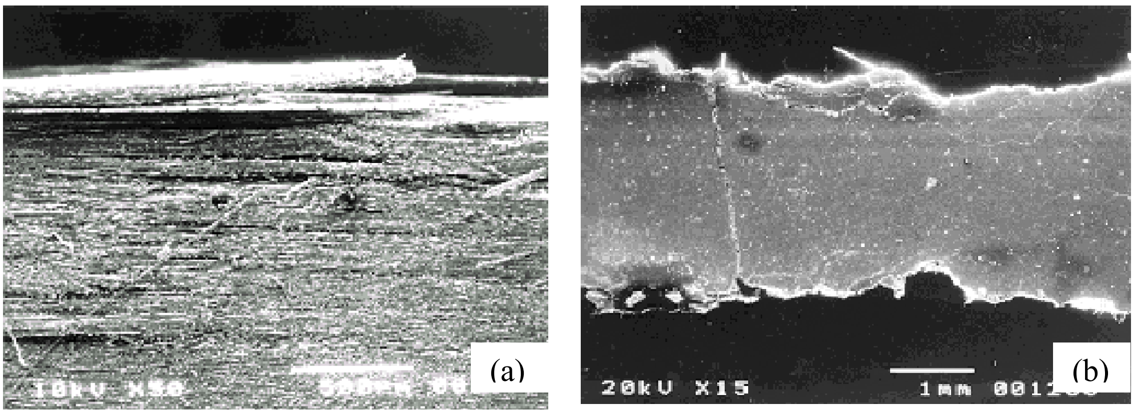

Fig. 3.3. The specimen after fatigue load (***u*** =const, ***R*** =-1) $\boldsymbol{\sigma_{L0}}$ = 367 MPa; $\boldsymbol{\sigma_{Lk}}$ = 220 MPa; ***N*** =2200000; (a) - side surface (x50); (b)- cross-section (x15).

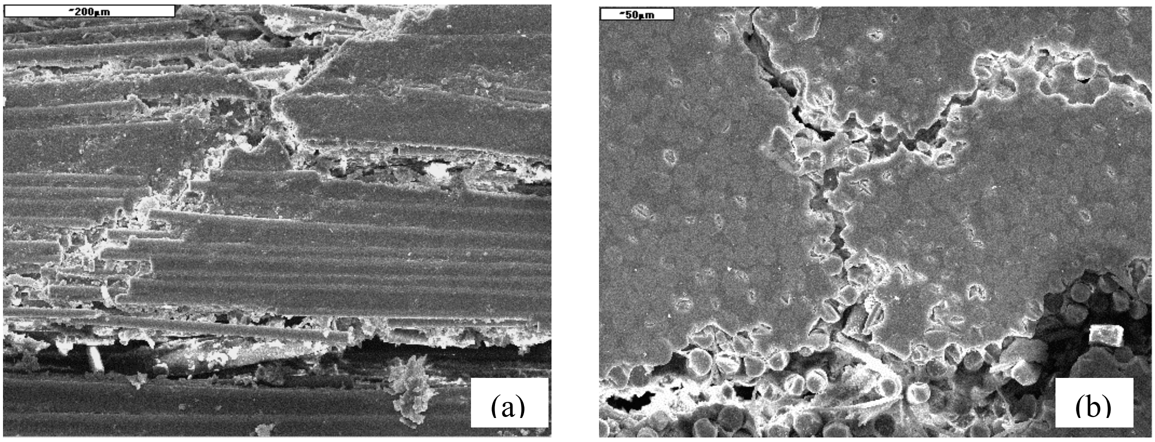

Fig. 4.1. The specimen after fatigue load (***u*** =const, ***R*** =0) σ_{L0} = 751 MPa; σ_{Lk} = 450 MPa; ***N*** =70000; (a) - side surface (x200); (b)- cross-section (x350).

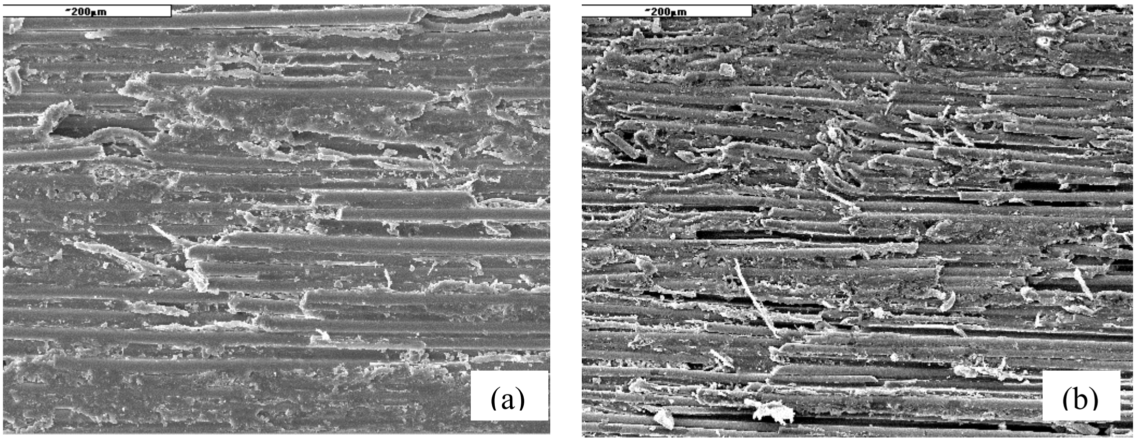

Fig. 4.2. The specimen after fatigue load (***P*** =const, ***R*** =0) side surface (a) σ_{L0} = 700 MPa; ***N*** =73000 (x200); (b)- σ_{L0} = 490 MPa, *N*=350000 (x200).

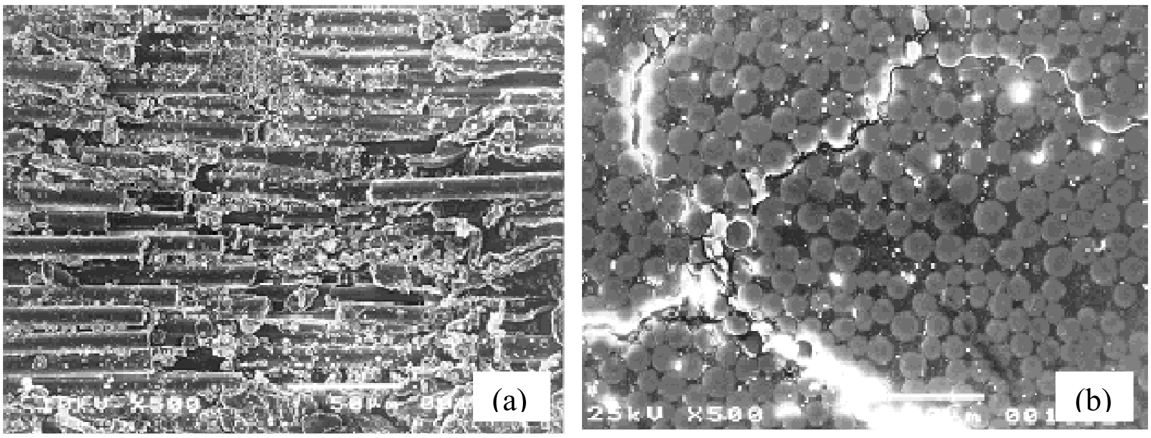

Fig. 4.3. The specimen after fatigue load (***u*** =const, ***R*** =-1) σ_{L0} = 367 MPa; σ_{Lk} = 220 MPa; ***N*** =2200000; (a) - side surface (x500); (b)- cross-section (x500).

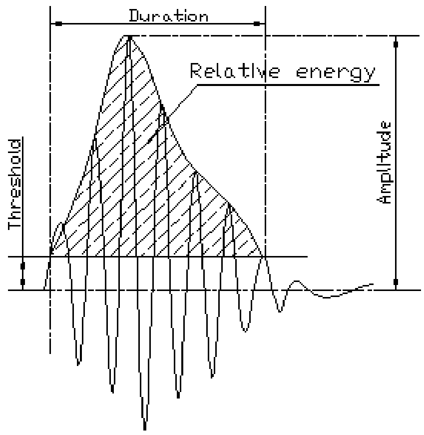

Fig. 5. Characteristic of AE signals "MARSE"

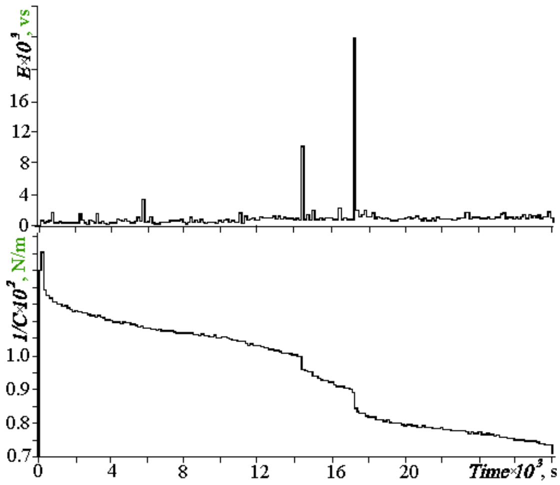

Fig. 6. Change of energy (E) signal and sample flexibility in fatigue test

CONCLUSIONS:

The analyses conducted above enables to formulate the following assumptions:

1. The arrangement of curves S_N (Fig. 1) shows the important influence of loading method to fatigue strength of a composite.
2. Mutual location of curves S_N depends on the realisation of dominating failure mechanisms during fatiguing,
3. Fractographic analysis enables to identify the existing mechanisms of failure.
4. The relation between the basic mechanisms of a composite failure and energetic level of AE signals, has been settled.
5. The possibility of AE application for monitoring of a composite failure has been presented here.

REFERENCES:

[1] Talreja R.: *Fatigue of Composite Materials.* Technomic Publiskin Comp., 1987.

[2] Ni, Qing-Qing, Jenen, Eiichi.: *Fracture behaviour and acoustic emission in bending tests on single -–fiber composites.* Engineering Fracture Mechanics v.56 no.6 Apr.1997 p. 779-796.

[3] Bohse. J.: *Acoustic emission characteristics of micro – failure processes in polymer blends and composite.* Composities Science and Technology v.60 no.8. 2000 p.1213-1226.

[4] Barchan A., Dzioba I., Wasyliw B.: *Stanowisko do badań wytrzymałości zmęczeniowej przy sterowanym przemieszczeniu.* Mat.XVII Symp.nt. Zmęczenie Materiałów i Konstrukcji – AT-R, Bygdoszcz 2000 p.29-36.

[5] Barchan A., Dzioba I.: *The research testing of orthotropic composite fatigue.* Fracture Mechanics and Physic of Construction and Structures. Kamieniar, Lviv 2000, Ukraine.

[6] Barchan A., Dzioba I.: *Statyczna i zmęczeniowa wytrzymałość kompozytu ortotropowego.* Przeglą Mechaniczny 2000 No.5,6 p.17-22 Poland.

[7] Barchan A.: *The analysis of fatigue damages in glass – fiber reinforced composite.* Physicochemical Mechanics of Material. Lviv 2001 (in print).