MECHANIKA TEORETYCZNA
I STOSOWANA
Journal of Theoretical
and Applied Mechanics
1, 32, 1994

FRACTURE TOUGHNESS TEST OF SHORT FIBRE COMPOSITES

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A detail study on the failure process of short glass fibre reinforced phenolic resin composite is presented. A fracture mechanics approach has been adopted and Mode I tests have been caried out. The effect of specimen orientation has been investigated. It has been shown that for samples with L-T orientation the fracture energy G_c weekly depends on the width to thickness ratio and samples thickness while for samples with T-L orientation the fracture energy depends on the geometrical parameters more pronouncedly. To follow the failure processes an acoustic emission technique including amplitude analysis of acoustic events has been applied. Three groups of acoustic events with different amplitude range have been distinguished. The observed changes in acoustic events amplitudes show that different mechanisms are involved in fracture processes. From acoustic emission studies it is shown that critical failure event may preceded the fracture of sample.

1. Introduction

Short fibre reinforced plastics are a new generation of materials which exhibit high strength accompanied by low plasticity. For these materials fracture toughness is one of the most important mechanical properties. However, the fracture toughness determination meet a number of problems which are not encountered when testing metals. These problems result from the structure of composite prepared by injection moulding technology. During injection the fibers in the skin layers are situated near in parallel to the direction of mould filling while in the core of sample the fibres are aligned near perpendicularly to the filling direction. Thus the short fibre composites exhibit a layered structure and the skin to core layer thicknesses ratio depends on the thickness of the composite sheet. For this reason the dimensions of sample and the W/B ratio may influence significantly the toughness and the fracture testing conditions should accommodate these features.

Another problem in fracture testing of short fibre reinforced composites concerns the identification of crack initiation. The linear load displacement characteristic with violent fracture where the beginning of fracture can be found under the maximum load appear in selected samples only. For most of them there is some nonlinearity which appears as a result of different failure processes which occur at the vicinity of the crack tip and the real initiation load is not defined exactly.

None of these problems are solved satisfactorily and up till now there exist no standard method for fracture tests on short fibre composites. The protocol for fracture testing of these material is under development by ESIS Task Group on Polymers and Composites. The aim of this paper was to undertake an investigation into the influence of sample geometry and crack orientation on fracture toughness and to study the failure processes of short fibre reinforced composites. The paper was partially realized within the frame of Round Robin organized by ESIS Task Group on Polymers and Composites.

2. Material and specimen preparation

The composite material employed was a phenolic short glass fibre reinforced composite IXEF 1022 supplied by Solvay – Belgium. The samples were machined from 2 mm and 5 mm thick sheets prepared by injection moulding technology. Compact specimens were machined with *L-T* and *T-L* crack orientation. The letter *L* denotes the longitudinal direction i.e. the mould filling direction while the letter *T* the transverse direction. The first letter denotes the notch direction while the second one the applied load direction. The machined notch was sharpened by sliding a razor blade across the notch. The widths of samples were 75 mm and 100 mm for the thicknesses 2 mm and 5 mm, respectively. After fracture of "big samples" some small samples were machined from leavings and the width of them was 36 mm for both applied thicknesses. The samples orientation and dimensions are given in Table 1.

Table 1. Specimens configuration

Thickness B [mm]	5				2			
Orientation	L-T		T-L		L-T		T-L	
Width W [mm]	100	36	100	36	75	36	75	36

3. Method of testing

There is no standardized methods for fracture testing of short fibre composites and the tests were performed in agreement with "Testing protocol to characterize the toughness of plastics" developed by Williams (1991) and "Appendix 2" to this protocol by Moore (1992). Details concerning fracture tests on polymers useful in composites testing too are given by Williams (1985).

The toughness was evaluated in terms of the energy release rate G_c and the critical stress intensity factor K_c. It should be noticed that "energy per unit area of crack at fracture initiation" instead of "energy release rate" is frequently used. The critical load at crack growth initiation which was used for fracture toughness estimation was taken in accordance with the approach by Williams (1991). For samples with linear load-displacement response up to fracture the maximum load is taken as a critical one. In the case of some nonlinearity just before the crack growth the critical load corresponding to the crack initiation was determined by the intersection of load displacement diagram with a straight line drown from the origin of diagram with the slope 5% less than the slope of linear part of load displacement diagram (Fig.1).

The samples were loaded using the FPZ 100 testing machine. To obtain the load point displacement the loading machine provided with a stroke transducer was used. Therefore the energy for G_c calculation was corrected for total loading system compliance. For this purposes the sample without notch was loaded and the compliance C_i was determined as it is shown in Fig.1a. The energy for correction U_i was estimated from C_i using the formula

$$U_i = \frac{1}{2}P^2 C_i \tag{3.1}$$

Thus the corrected fracture energy is

$$U = U_Q - U_i \tag{3.2}$$

where U_Q is shown in Fig.1b.

In both diagrams an initial nonlinearity is corrected as it is shown in Fig.1.

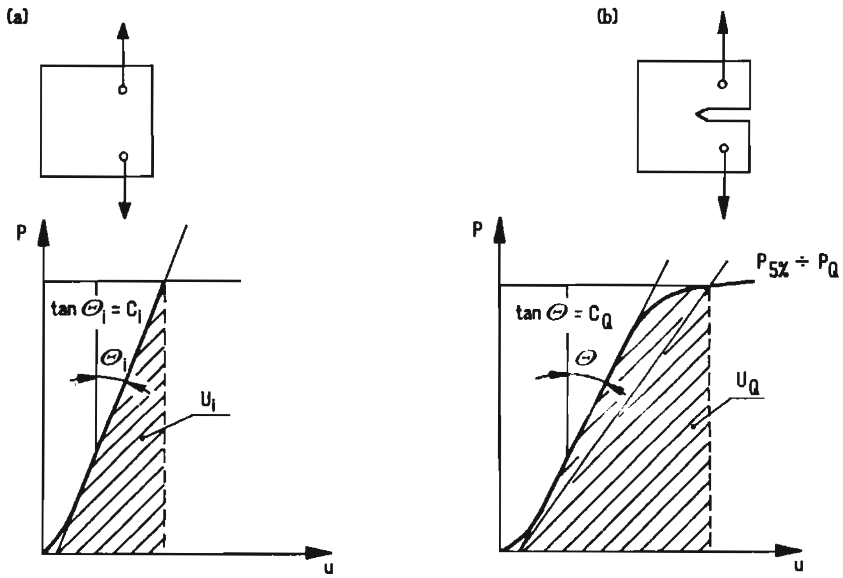

Fig. 1. Specimens used for fracture tests: (a) without notch for compliance measurement, (b) with notch for fracture energy determination

The energy per unit area of crack G_c at fracture initiation was calculated from the formula for energy U via

$$G_c = \frac{\eta_e U}{B(W-a)} \tag{3.3}$$

while K_c was calculated from the formula

$$K_c = \frac{P}{B\sqrt{W}} f \tag{3.4}$$

where η_e and f depend on sample geometry and are given by Kapp et al. (1985).

4. Results

The results for tested material calculated in agreement with the approach by Williams (1991) in dependence of samples orientation and dimensions are given in Table 2.

Table 2. Fracture toughness of short fibre composites in dependence on orientation and samples dimension

B [mm]	5				2			
W [mm]	100		36		75		36	
Orientation	L-T	T-L	L-T	T-L	L-T	T-L	L-T	T-L
G_c[KJm^{-2}]	$8.46^{\pm 0.35}$	$15.2^{\pm 6.1}$	9.09	6.09	$11.3^{\pm 0.2}$	$3.2^{\pm 1.4}$	12.1	6.7
K_c[MPa$\sqrt{m}$]	$8.69^{\pm 0.25}$	$10.9^{\pm 2.1}$	8.29	6.17	$11.5^{\pm 0.5}$	$6.4^{\pm 1.2}$	10.7	6.9

The data presented in Table 2 prove that orientation of samples has influenced the failure behavior of tested composite. The fracture toughness of samples with L-T orientation increases slightly with the decrease in dimensions of both thickness and width. However the dependence of thickness on toughness is more pronounced. It should be noticed that the scatter of results for this orientation is relatively low.

On the contrary the toughness of samples with T-L orientation decreases with the dimensions decrease. Significant scatter of results made unable the discussion of the influence of samples dimensions on toughness parameters.

The discrepancies which are observed in fracture testing results of discontinues fibre composites show that the detailed analysis of load – load point displacement diagrams is necessary. In tested composites three basic loading displacement curves may be seen. They are:

- Linear up to failure and unstable crack propagation
- Linear with some nonlinearity just before failure
- Linear with a number of "pop-in" events.

The term "pop-in" means discrete crack extension.

In each set of samples listed in Table 1 all three shapes of diagrams might be observed. This means that the true initiation load cannot be defined by the procedures given by Williams (1991) and Moore (1992).

The failure processes in this type of composites involve a number of mechanisms including matrix plastic deformation and failure, fibre pull out and/or breakage and bunches of fibres pull out. These elementary events are combined in a way very complicated for the description of damage growth and fracture. At a sufficient stress level some of these mechanisms may results in critical events leading to crack initiation. In composites with visco elastic matrix it is probable that the critical event and crack initiation do not coincide and take place not at the same time.

To follow the failure processes the acoustic emission (AE) method, including amplitude analysis of AE signals, was employed. This method was applied with good results to analysis of interlaminar fracture mechanisms in long fibre composites (cf Gołaski, 1992). For this purposes GACEK processor together with the broad band sensor was used. The AE signal was evaluated as a number of events. The events were counted versus time in 15 levels with the difference of $6dB$ between adjacent levels. Thus AE amplitude analysis was made in the range $6 \div 90dB$. Next different low and high level filters were used to select proper AE events for further analysis. AE events, loading and displacement were recorded at the same time. Next the diagrams of load and AE events vs. load – point displacement were drawn.

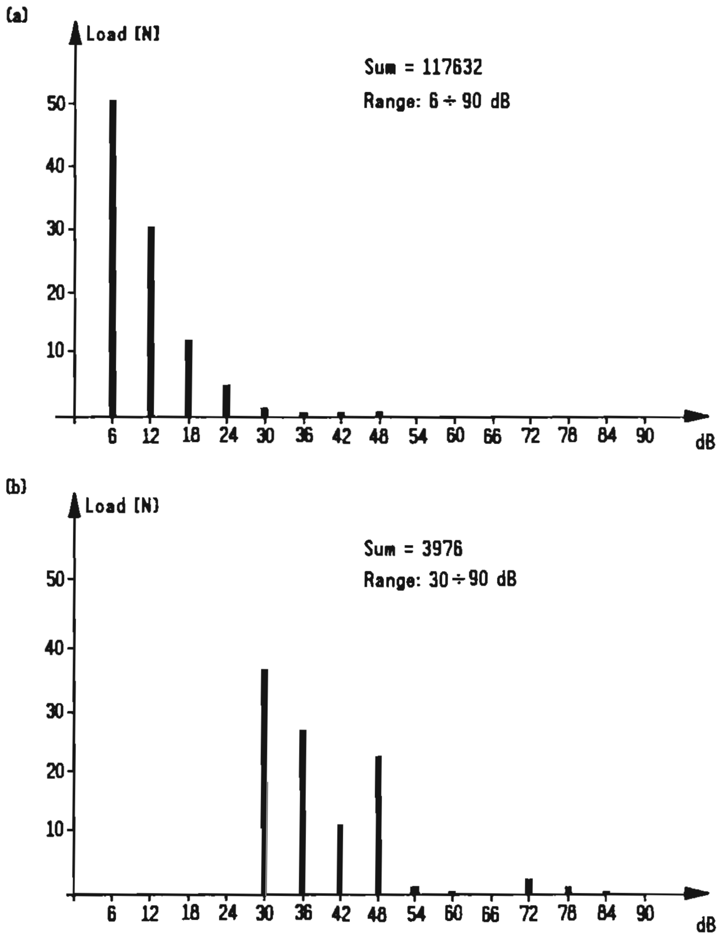

Fig. 2. Acoustic emission amplitudes distribution: (a) amplitudes $\geq 6dB$, (b) amplitudes $\geq 30dB$

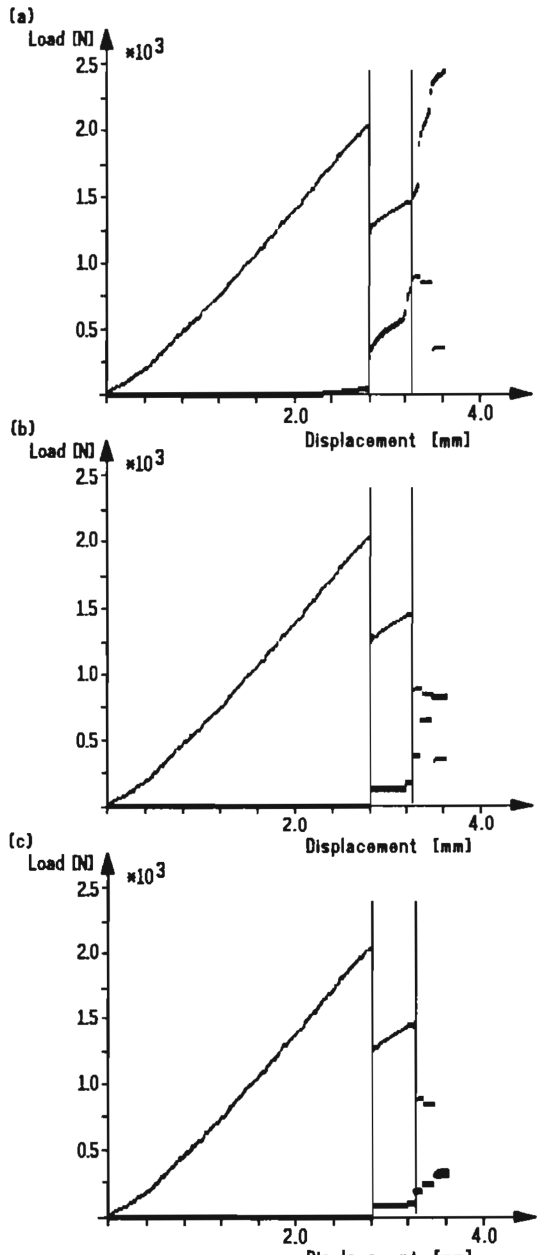

Fig. 3. Typical load and acoustic events versus displacement diagram for linear behaviour of samples: (a) amplitude events $\geq 6dB$; (b) amplitude events $\geq 30dB$; (c) amplitude events $\geq 54dB$

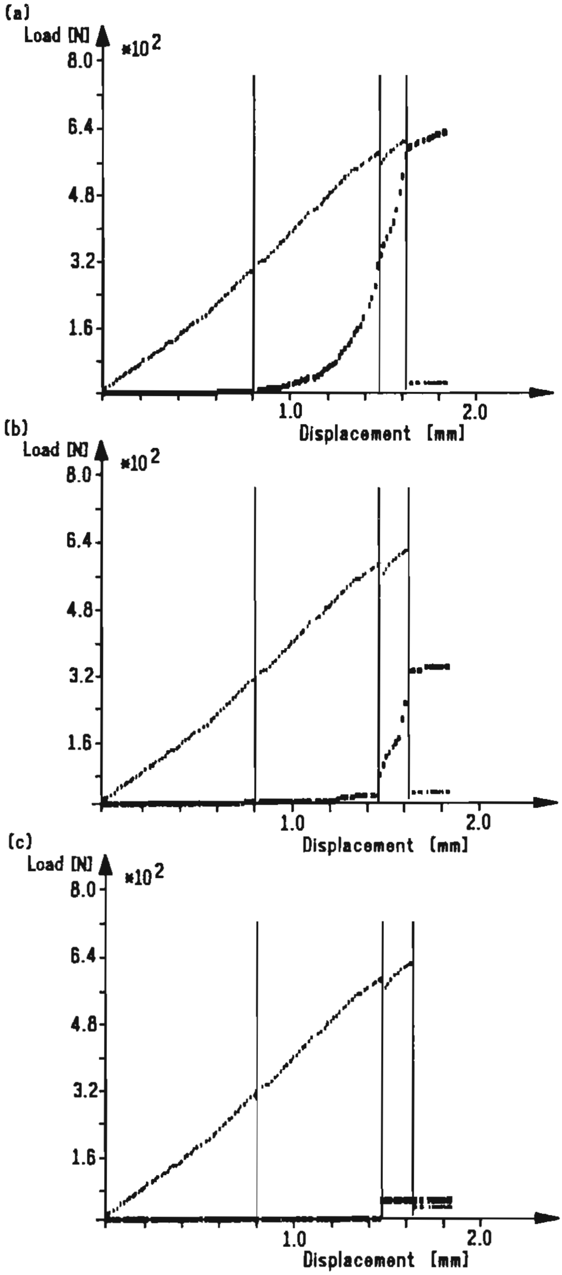

Fig. 4. Typical load and acoustic events versus displacement diagram for samples in which some nonlinearity on loading trace before fracture can be seen: (a) amplitude events $\geq 6dB$; (b) amplitude events $\geq 30dB$; (c) amplitude events $\geq 54dB$

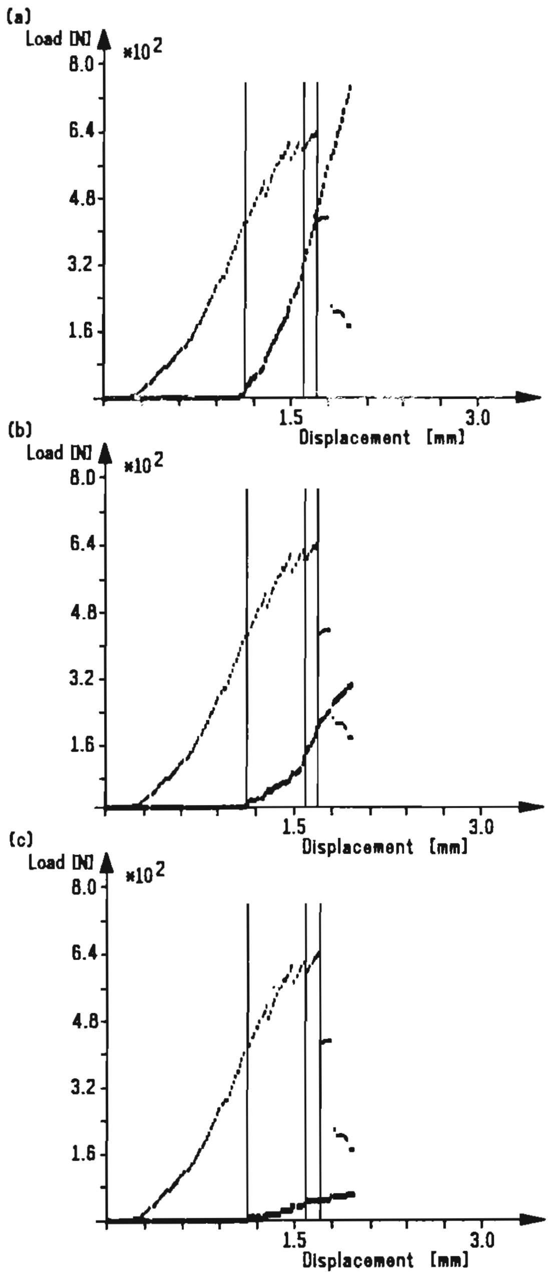

Fig. 5. Typical load and acoustic events versus displacement diagram for samples in which on loading trace "pop-in" took place: (a) amplitude events $\geq 6dB$; (b) amplitude events $\geq 30dB$; (c) amplitude events $\geq 54dB$

The amplitude distribution of AE events shown in Fig.2a exhibit three groups of amplitudes well separated from each other in all tested samples regardless their thickness and width. The groups of AE events are: low amplitudes (LA) group including events with amplitudes in the range $6 \div 24dB$, medium amplitudes (MA) in the range $30 \div 48dB$ and high amplitudes (HA) with amplitudes $\geq 54dB$. Most of the events were these of low amplitudes and to show MA and HA group of events $24dB$, a low level filter was applied to cut off LA events. The histogram of amplitudes of the range $30 \div 90dB$ are shown in Fig.2b. The presented amplitude distribution suggests that three mechanisms dominate in the failure process of tested composite.

To follow the failure processes, on the diagrams of load vs. displacement the diagram of number of AE events vs. displacement were superposed. Three low level filters were applied and thus the traces of total number of events, of the MA and HA events sum and of HA events only are given. In Fig.3 to Fig.5 three typical behaviours of sample are shown.

In Fig.3 results from sample with linear load characteristic up to failure and unstable crack propagation are presented. Some low amplitude AE events started under load equal to $\sim 0.8P_{\max}$. A burst type of AE was observed at first cracking. AE events in all three groups can be seen. Every next cracking is accompanied by sudden increasing in AE events in three selected ranges of amplitudes.

In Fig.4 load and AE behavior of sample is given where some nonlinearity of load diagram before fracture can be seen. AE activity starts under load $\sim 0.5P_{\max}$ where a knee on the loading diagram appears. The beginning of nonlinearity coincides with increasing in acoustic emission and a number of MA events appeared. First HA events were observed when "pop-in" took place and from this time a significant AE activity in MA range occurred. However, when sample fractured there was no change in HA events.

Fig.5 presents the results from sample in which during loading a number of "pop-in" events took place. Each "pop-in" was accompanied by acoustic emission increasing in all three groups of amplitudes. It is interesting to notice that during fracture of sample, as in the sample presented in Fig.4, no HA events took place. At that time no relative extremum on a total AE events curve was observed. However the fracture of sample was preceded by a significant increasing in MA acoustic events.

5. Conclusions

The values of Mode I fracture energies have been determined for short glass fibre reinforced composite IXEF 1022 as a function of specimen orientation and dimensions. An analysis of failure processes employing the acoustic emission technique has been made. The amplitude analysis of acoustic events has been made to find the failure mechanisms which occurred in tested composite.

The main conclusions are:

- The orientation of samples seriously affect the results of fracture tests
- For samples with *L-T* orientation the fracture toughness increases with the samples dimensions decrease
- For samples with *T-L* orientation the fracture toughness decreases with the samples dimensions decrease and a significant scatter of results is observed
- Acoustic emission together with the acoustic signals amplitude analysis is a useful technique for composites testing
- Three main failure mechanisms take place in fracture of tested composite
- The failure events which emitted high amplitude acoustic signals do not lead directly to fracture of sample, however, they seem to be the critical events for fracture
- The failure events which are accompanied by high amplitude AE release the failure processes accompanied by medium amplitude acoustic emission. This failure process leads to samples fracture
- The critical failure events may preceded the failure of sample.

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Ocena odporności na pękanie kompozytów wzmocnionych włóknem krótkim

Streszczenie

W pracy przedstawiono wyniki badań odporności na pękanie kompozytu wykonanego z żywicy fenolowej wzmocnionej krótkim włóknem szklanym. Badania przeprowadzono na próbkach z karbem obciążanych zgodnie ze sposobem I. Analizowano wpływ geometrii próbek na wyniki próby odporności na pękanie. Stwierdzono, że w przypadku próbek o orientacji *L-T* odporność na pękanie w małym stopniu zależy od rozmiarów próbki i jej grubości. Natomiast dla próbek o orientacji *T-L* geometria próbek może mieć istotny wpływ na mierzone wartości. Przeprowadzono analizę procesu pękania stosując metodę emisji akustycznej z analizą amplitudową sygnałów akustycznych. Stwierdzono występowanie trzech grup sygnałów akustycznych świadczących o udziale kilku mechanizmów uczestniczących w procesie pękania. Wskazano na podstawie analizy sygnałów akustycznych, że krytyczne zdarzenia pękania mogą wyprzedzać pęknięcie próbki.

Manuscript received October 1, 1993; accepted for print October 14, 1993