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# Virtual Crack Closure Technique on Delamination Fracture Toughness of Composite Materials Based on Epoxy Resin Filled with Micro-Scale Hard Coal

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In the present paper, the delamination fracture toughness of composite materials on cantilever beams was studied. The cantilever beams were assumed to be epoxy resin filled with hard coal and recently developed a new composite material model was used. Accordingly, the composite materials were based on epoxy resin as a matrix and two types of hard coal as fillers with additions of 4.32, 7.5, and 10.68 vol.%. The fracture toughness of epoxy-hard coal composite cantilever beams was investigated numerically by using ANSYS® finite element analyses package program. Mode I fracture toughness (critical strain energy release rate) in the neighborhood of the crack zone was found by using virtual crack closure technique for critical displacement values. The influences of the types and volumes of the hard coal fillers on the strain energy release rate were presented. The critical strain energy release rate increased at 10.8% when the volume ratio of anthracite coal was increased from 4.32% to 10.68%. Model verification of the finite element analysis was performed with an analytical solution in literature and the difference was determined as 3.75% and also this pointed the precision of the present finite element analysis.

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## 1. Introduction

In the polymer composites, compositional and microstructural gradients are intended to admit an optimum combination of component properties, for example weight, surface hardness, wear resistance, impact resistance, surface and volume resistance and toughness [1]. These material properties are important in engineering application for materials selection and they are used in a variety of applications, including the aerospace, automobile, marine industries, and many other fields. Although polymer composites have been in use for decade, fully understanding and accurately prediction of their failure mechanisms remains a significant challenge. This study is addressed to the most common modes of failure: delamination. This study focuses on delamination fracture toughness in the vicinity of the crack zone and to the calculation strain energy release rates for polymer composite materials using the virtual crack closure technique (VCCT). A cantilever beam (CB) was modeled using finite element model in ANSYS commercial software. As a pure mode I problem, the cantilever beam was loaded by critical displacement. In the literature, delamination is generally assumed to occur in the interfaces of adjacent plies and to treat as a fracture process in the anisotropic layers [2–5]. But delamination can onset due to manufacturing or to low velocity impact of dropping tools or runway debris. Over the past two decades, the use of fracture mechanics has become common practice for characterizing the onset and growth of delaminations [6–8]. Crack onset, propagation, and growth at various material interfaces are of interest to a large community. In the current paper the attention is to predict delamination onset, propagation and growth in polymer composite material which is based on epoxy resin filled with hard coals. The influences of the type and volume of hard coals on the strain energy release rate were investigated by using VCCT.

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## 2. Virtual crack closure technique

Many of methods use singular elements to develop a stress or energy at the crack tip. However, VCCT can be done with ordinary plane elements and uses the strain energy release rate ($G_{Ic}$) to determine cracking instead of stress. This offers many advantages, especially with regards to element size and ability to use the same mesh at each loading step instead of having to remesh in order to incorporate singular elements at the moving crack tip. The first VCCT approach to compute strain energy release rates, starting from forces at the crack tip and relative displacements of the crack faces behind it, was proposed for four noded elements by Rybicki and Kanninen [9]. After that, Shivakumar et al. [10] extended it by using three-dimensional (3D) cracked bodies. A comprehensive review of VCCT formulae for different element types was given by Krueger [11]. It is obvious that a crack growth period should be known very well for a reliability demonstration. For general 3D objects, the critical point as well as crack growth itself may be investigated by a finite element method (FEM) as in the present paper.

## 3. Analysis of composite cantilever beam structure

The geometry of the cantilever beam used is as shown in Fig. 1a. The initial delamination is located at the middle of the specimen and it has a length of 30 mm.

The numerical model of cantilever beam was divided into a finite number of elements by satisfying the equilibrium and compatibility at each node. A finer mesh was used in the delamination zone. SOLID185 element was used in the model and the mesh detail of cantilever beam can be seen in Fig. 1b.

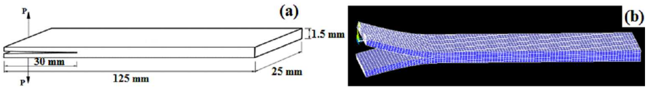


Fig. 1. The cantilever beam: (a) dimensions, (b) finite element mesh.

The anthracite coal fillers were mined in Kuzbas of the Kuznetsk Basin and the second type of hard coal was acquired from "Zofiówka" coal mine [12]. Coals were classified as anthracite coal and hard coal. Basic characteristics of component materials are shown in Table I. Epoxy resin Epidian 6 was used as thermosetting polymeric matrix and its elasticity modulus ($E_{epoxy}$) was 3.24 GPa and the Poisson ratio ($\nu_{epoxy}$) was 0.25.

TABLE I

Basic characteristics of anthracite coal and hard coal.

| Properties | Anthracite coal, type 32 | Hard coal, type 35 |
|---|---|---|
| carbon contents [%] | 87.9 | 88.5 |
| ash contents [%] | 3.37 | 16.78 |
| specific surface [m$^2$/g] | 0.146 | 0.939 |
| range of grain size [µm] | $d_{10\%} = 20.12$; $d_{50\%} = 132.64$; $d_{90\%} = 358.36$ | $d_{10\%} = 2.92$; $d_{50\%} = 17.93$; $d_{90\%} = 64.25$ |
| density [g/cm$^3$] | 1.37 | 1.40 |

Then, the anthracite and hard coal ratios of 4.32, 7.5, and 10.68 vol.% were chosen and added into the epoxy resin. Using the gravitational casting methods, the specimens were obtained and one-dimensional gradient of component materials content in liquid matrix [12].

## 4. Analysis results and discussion

In the present study, the displacement load was adopted following the presented by Sun et al. in 1998 [13] and the $G_{Ic}$ distribution was calculated from the model for an applied displacement of 8.1 mm. The distribution of displacement and the von Mises stress on the 4.32% anthracite coal cantilever beam were presented in Fig. 2a and Fig. 2b, respectively. The maximum von Mises stress (red zone in Fig. 2b) always occur at the neighborhood of the crack tip. The displacement and von Mises stress distribution shapes were similar for the other coal types and volume ratios. The $G_{Ic}$ values for 0% anthracite coal listed in Table II reveals that for initially straight delamination front $G_{Ic}$ is maximum at the longitudinal centerline of the cantilever beam and minimum at the specimen edges.

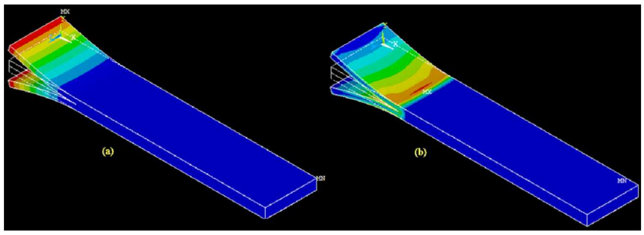


Fig. 2. 4.32% Anthracite coal: (a) displacement, (b) the von Mises stress distribution.

TABLE II

Distribution of $G_{Ic}$ for the cantilever model.

| Distance from centreline [mm] | $G_{Ic}$ for 0% Anthracite coal/ hard coal | $G_{Ic}$ for 10.68% Anthracite coal | $G_{Ic}$ for 10.68% hard coal |
|---|---|---|---|
| 0 | 0.41958 | 0.48943 | 0.51017 |
| 2.5871 | 0.41743 | 0.48677 | 0.50719 |
| 5.763 | 0.41385 | 0.48202 | 0.50243 |
| 7.537 | 0.40273 | 0.46790 | 0.48740 |
| 10.111 | 0.33917 | 0.38899 | 0.40074 |
| Average | 0.39855 | 0.46302 | 0.48158 |

The influences of coal type and coal ratio (vol.%) on the critical strain energy release rate ($G_{Ic}$) are presented in Fig. 3. The $G_{Ic}$ of the polymer composites cantilever beam were examined and these values were compared with the non-coal (0% anthracite coal, 0% hard coal) cantilever beam. The $G_{Ic}$ value was 0.41958 kJ/m$^2$ for the sample added neither anthracite coal nor hard coal powders. These values were determined as 0.48943 kJ/m$^2$ and 0.51017 kJ/m$^2$ for 10.68 vol.% anthracite coal and 10.68 vol.% hard coal structures cantilever beam respectively (Fig. 3). In general, the $G_{Ic}$ value increased as increasing the volume ratio of graphite powders.

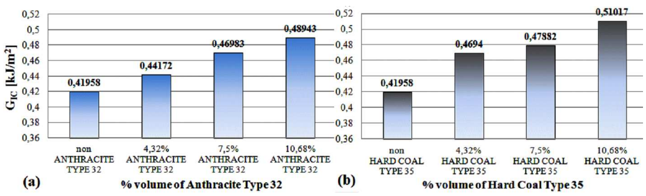


Fig. 3. Effects of the coal powder volume ratios on the critical strain energy release rate: (a) anthracite coal, type 32, (b) hard coal, type 35.

As seen in Fig. 3a the $G_{Ic}$ value increased up to 10.80% when the volume ratio of anthracite coal increased from 4.32% to 10.68%. This increment was calculated as 8.69% for hard coal and it can be seen in Fig. 3b. The highest $G_{Ic}$ value was determined in hard coal cantilever beam and this result presented that hard coal powder was compatible with resin and hard coal cantilever beam responded much better load.

## 5. Validation of the finite element analysis

The critical strain energy release rate ($G_{Ic}$) distribution values were determined by FEM simulation. Model verification of the finite element analysis can be compared with the results obtained by Sun et al. in 1998 [13]. In the present study, model geometry was adopted in the literature to make comparisons however the behavior of the cantilever beam in the structures are assumed to be polymeric composite and recently developed a new polymeric composite model [12] is used. In the literature specimen material properties are $E_{xx} = E_{yy} = 54.5$ GPa and $\nu_{12} = 0.08$ and initial delamination length 30 mm. The present FEM analysis was applied to the composite material and the result were compared with the analytical solution [14] and FEM solution [13] as shown in Table III. The differences between presented FEM and analytical solutions were determined as 3.75% and this pointed at the precision of the presented FEM analysis.

TABLE III

Values of critical strain energy release rates. Analytical-numerical solution for composite cantilever beam ($E_{xx} = E_{yy} = 54.5$ GPa and $v_{12} = 0.08$).

| Solution comparisons | Average $G_{Ic}$ [kJ/m$^2$] | Differences [%] |
|---|---|---|
| analytical solution [14] | 1.3823 | 0.00 |
| FEM solution [13] | 1.3541 | 2.08 |
| presented FEM solution | 1.3324 | 3.75 |

## 6. Conclusion

Polymer composites are materials whose behaviors are difficult to predict by using numerical methods especially in presence of delamination. Nevertheless, the finite element method used with the virtual crack closure technique can provide effective information in terms of structure behavior. In this study, the critical strain energy release rate ($G_{Ic}$) values for cantilever beam specimens made of recently development polymer composite was examined. The composite material based on epoxy resin as a matrix and two type of hard coal as fillers with additions of 4.32, 7.5, and 10.68 vol.%. The influences of the types and volumes of the hard coal fillers on the critical strain energy release rate were investigated. Also, the presented finite element analysis was proven by comparison with analytical solutions in the literature and the difference was determined as 3.75%.

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