MODIFICATION OF ENERGY RELEASE RATES IN TEXTILE REINFORCED THERMOPLASTIC COMPOSITES TO CONTROL DELAMINATION CHARACTERISTICS

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Abstract
In the this study a modification strategy is presented to adjust the interlaminar properties and the corresponding delamination characteristics of a textile reinforced thermoplastic composite, consisting of glass fibre reinforced polypropylene. The modification is achieved by using perforated Polytetrafluoroethylene (PTFE) foils to reduce the interlaminar contact area (ICA), where the investigated ICAs vary from 0 % to 100 %. Double Cantilever Beam (DCB) and End Notched Flexure (ENF) experiments are used to determine the resulting mode I and II delamination energy release rates. An adapted experimental method based on digital image correlation (DIC) is presented which to correlate specimen deformations during the experiments and crack tip propagation to assess energy release rates with respect to ICA. The results are used to evaluate the different interface modifications and their impact on the delamination characteristics. With the DIC based experimental method an automated crack propagation measurement is achieved. The elaborated strategy to modify the ICA is well suited to adjust the interlaminar properties and the corresponding delamination characteristics. The presented methodology enables an innovative approach for the design of crash and impact loaded structural components with improved energy dissipation characteristics.

1. Introduction

Textile reinforced thermoplastics are used increasingly in multi-material composite structures due to their excellent mechanical properties, such as strength and energy absorption, in combination with good media resistance and recycling compatibility. Hence this class of material is predestined for automotive applications [1–3]. Significant design drivers are the increasing crash and impact requirements. Therefore, the crash and impact characteristics of textile reinforced thermoplastic glass/polypropylene composites and especially their delamination behaviour has been in focus in recent years [4–8]. In the presented work, a modification strategy is investigated to adjust the interlaminar mechanical properties and the corresponding delamination characteristics with the aim of more advantageous structural energy absorption characteristics. For that, perforated PTFE foils are used to adjust the interlaminar properties by reducing the ICA. The interface modifications vary from 0 % to 100 % energy release rate with respect to an unmodified setup, where the textile architecture implies a direction dependent property profile [9]. The investigations are based on an adapted experimental method, using DIC to detect the delamination propagation in DCB and ENF experiments.

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2. Experimental Set up

2.1. Investigated material and interface modification concept

A layer-wise 3D textile reinforced composite material is used in the presented investigation, namely a multi-layered weft knitted fabric (MKF). Here, the material configuration of glass fibres and a polypropylene (PP) matrix system was realised employing commingled hybrid E-glass-polypropylene yarns with a fibre-fineness of 1400 tex in 1- (warp) and 2-direction (weft) and a loop yarn of 139 tex, representing a layerwise 3D-reinforcement. The result is an equal mass share of 42 % (0° and 90°) and 16.5 % (loop) and the fibre volume fraction results in 55 %. A detailed description of the textile architecture and additional material properties can be found in [2, 5, 10]. To manufacture the specimen panels an autoclave at 200 °C and a pressure of 6 bar was used. Due to the non-crimped textile architecture of the investigated MKF, the interface setup and according waviness varies in 0° and 90° direction. This fact has been discussed in detail in [9] for a carbon fibre (CF) based MKF with an epoxy (EP) matrix system. The textile structure is given in Figure 1. Therefore, delamination characterisation has been conducted for both directions.

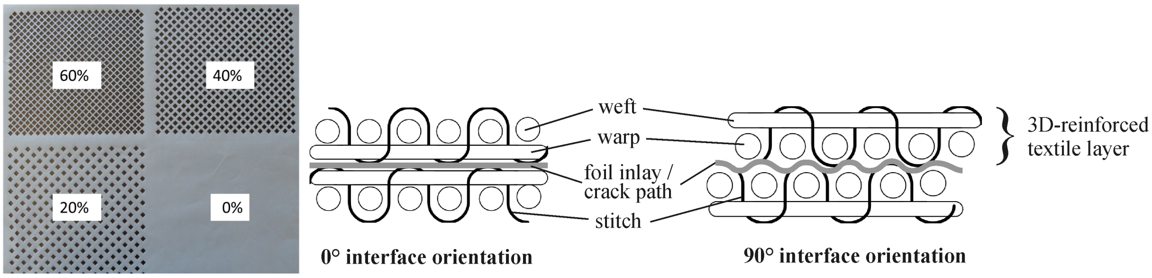

Figure 1. Left: Perforated foils with different interlaminar contact areas (ICA); right: MKF textile structure [9]

The interface modification is achieved by perforated PTFE foils with a thickness of 75 μm placed between the textile layers. PTFE is non adhesive with PP and the thermal expansion coefficient nearly equals the one of PP leading to negligible residual stresses during manufacturing. A low coefficient of friction minimises energy dissipation during delamination testing and hence the error for global energy balances in the experiments.

The interlaminar contact area (ICA) [11, 12] is used to quantify the applied interface weakening, where five configurations are investigated: 0 %, 20 %, 40 %, 60 % and 100 %. 0 % corresponds to a non-perforated foil and 100% to no foil layer (Figure 1). The quadratic perforations exhibit an edge length of 4 mm and are positioned in 45° to each other.

2.2. Energy release rate measurement using DIC

The determination of mode I and II critical energy release rates $G_{Ic,IIc}$ in pre-cracked specimens is based on the application of a force F in a mode related direction. As a result the crack is forced to propagate. Similar testing setups for both modes can be found for example in [10]. The critical energy release rate is calculated by relating the fracture work W_F to the generated fracture surface $A = B \cdot \Delta a$:

$$G_{Ic,IIc} = \frac{W_{F_{I,II}}}{B \cdot \Delta a} , \qquad (1)$$

with B denoting the constant specimen width and a the crack length. W_F is seen as result of the systems total energy less the elastic deformation energy.

The visual detection of crack propagation is realised using the DIC system ARAMIS 5M (GOM mbH) for both modes I and II. For the deformation measurements a frame size of 2448 px × 2050 px with facet sizes of 15 px × 15 px (0.36 mm × 0.36 mm), facet distances of 13 px × 13 px (0.31 mm × 0.31 mm) at a frame rate of 0.5 Hz is applied. Especially for mode II, the measurement of crack propagation length is challenging. In contrast to mode I, where a visible gap is created, the crack surfaces slide on each other under compression and complicate crack front detection.

In the DCB test setup, displacement in direction of loading of the specimen levers can be directly used to calculate the crack tip opening. In contrast, in the ENF experiments different modes of motion have to be taken into account. The mode II dislocations based on DIC measurements are indicated exemplarily at four positions (pairs of circles) in Figure 2 a) at different points in time during the experiment. For crack propagation measurements, rotations and bending deformations have to be analysed. With crack occurrence, the relative displacements of the upper and lower lever have to be considered additionally (Figure 2 b). An in-house MATLAB code was used to analyse this behaviour. By measuring the specimen deformation during loading, the fracture area and thus the crack propagation is calculated for each loading step. For the identification of the crack front failure strain based dislocation criteria is used:

$$\delta^{I}_{max} = \varepsilon^{f}_{33}\,\delta_{ini} \quad \text{(mode I)}, \qquad \delta^{II}_{max} = \sin(\gamma^{f}_{13})\,\delta_{ini} \quad \text{(mode II)}, \tag{2}$$

where $\delta^{I,II}_{max}$ denotes the dislocation where crack opening for the respective modes I or II is assumed. Failure strains ε^{f}_{33} and γ^{f}_{13} have been determined in [5]. The initial distance between the upper and lower lever points δ_{ini} equals 3.6 mm.

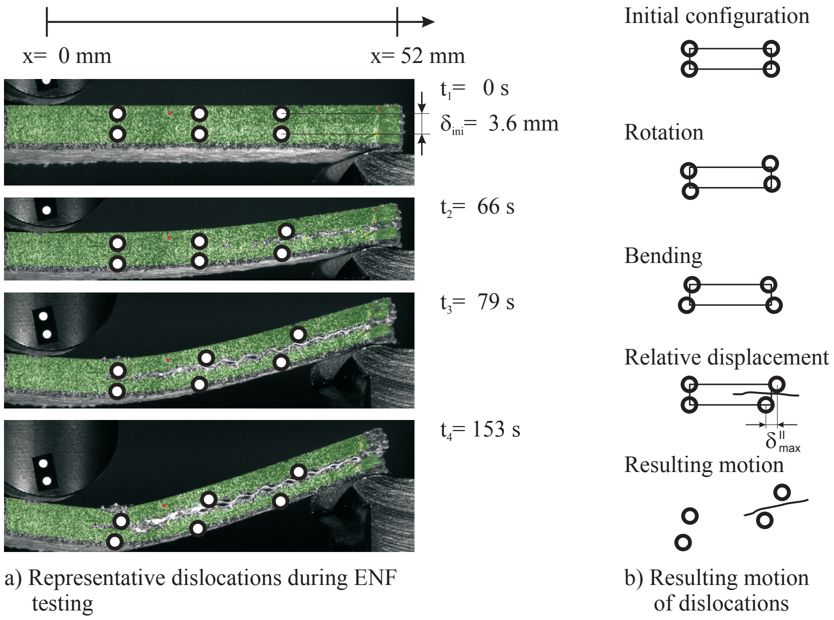

Figure 2. Delamination crack front detection in ENF experiments based on DIC

2.3. Results and Discussion

Visual crack observation

The DIC enables the visual crack observation by using the above mentioned algorithm which separates the different motion modes and extracting the relative displacement of the upper and lower lever. As a result crack propagation is examined versus displacement of the testing machine. Figure 3 shows exemplary force-displacement curves and the associated crack propagation of DCB and ENF experiments with ICA=100 %.

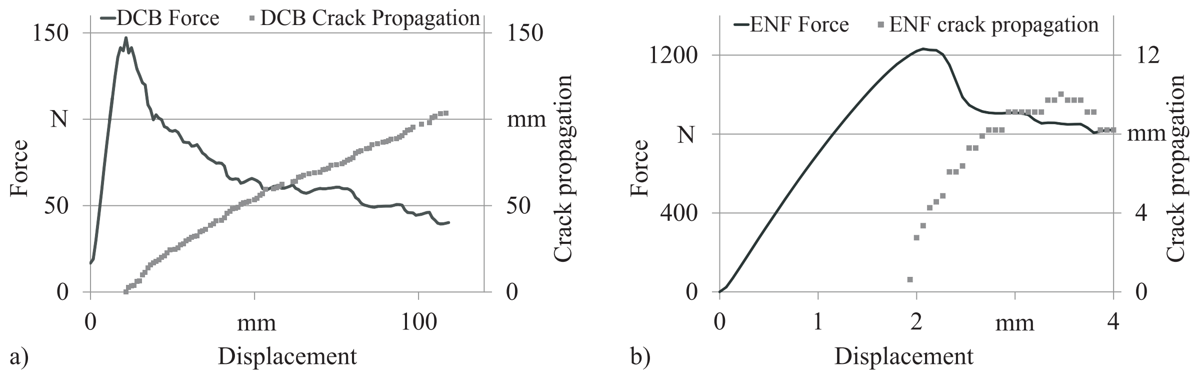

Figure 3. Representative force-displacement and crack propagation-displacement curve for a) DCB and b) ENF test with ICA= 100 %

The DCB specimen deforms elastically until a maximum force level at approximately 16 mm displacement with a subsequent force reduction. The loss of stiffness corresponds to the energy absorption by crack propagation, leading to a continuously ascending crack length and a descending force. The DIC supported crack measurement enables the determination of the crack rate, which is defined as crack propagation with respect to displacement.The measured crack rate results in a constant value of about 0.95 mm/mm and the observed crack propagation length is 103 mm.

The structural response of the ENF specimen differs from the DCB specimen. A significant non-linear force-displacement response until maximum force at approximately 1200 N is observed. In correspondence to the DCB experiments, a subsequent force drop is associated with crack propagation. That leads to the conclusion, that a non-linearity criteria determining crack initiation as recommended in [13] unidirectional carbon- and glass fibre reinforced epoxy is not appropriate for the investigated MKF with PP-matrix. In contrast to the DCB experiments, the crack propagation velocity is not constant, decreasing significantly with the crack rate, varying from 38.2 mm/mm to 0 mm/mm. With the crack front arriving at the compression dominated area under the fin, crack propagation is stopped and the delamination length reaches a plateau at a maximum of approximately 10 mm.

Energy release rate

Mode I and II energy release rates are investigated with respect to varying ICA and interlaminar fibre orientations. The respective values are calculated using Equation 1. Mode I results are in progressive correlation with the ICA for both 0° and 90° configurations (Figure 4) and expectably increase with a rising ICA. In contrast to the findings in [9], 90° energy release rates are higher slightly then 0° ones.

Mode II results indicate a contrary relation of 90° and 0° energy release rate values in comparison to Mode I. The tendency of lower 90° values is in agreement to the CF-EP results in [9]. In general mode II energy release rates are higher than mode I ones, but both show a non-linear dependency between the energy release rates and ICA.

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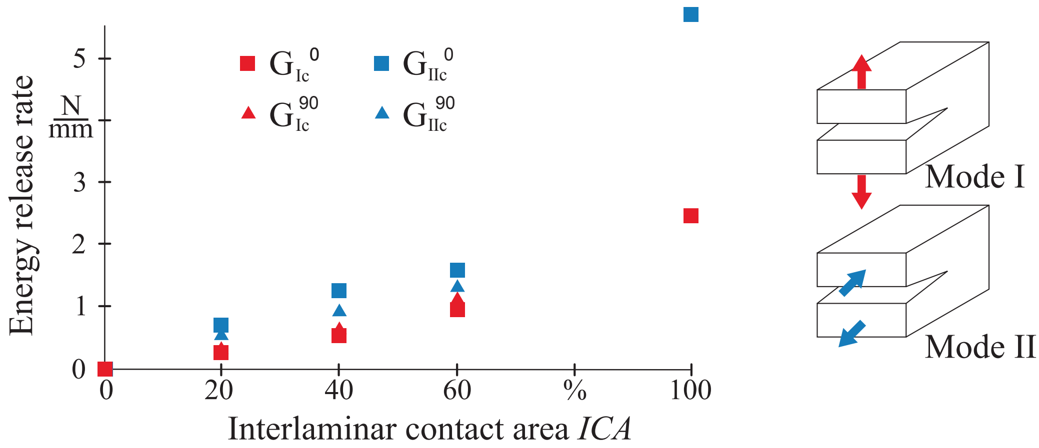

Figure 4. Energy release rates G_{IIc} of 0° and 90° interfaces

3. Conclusion

In the presented study the delamination behaviour of textile reinforced thermoplastic composites with varying interlaminar properties has been investigated. A perforated PTFE foil between the plies was used within the manufacturing process and is well suited to control the delamination behaviour by adjusting the ICA.

The delamination behaviour of specimen with different interlaminar properties can be analysed with DCB- and ENF-tests using a DIC based method. This method enables a visual crack length measurement during the experiments. Furthermore, in combination with the dissipated energy the crack length can be employed to calculate energy release rates for the investigated configurations. It has been shown, that the established non-linearity criteria determining crack initiations are not appropriate for the investigated thermoplastic matrix based composite due to the pronounced non-linear elastic deformation and non-brittle failure behaviour.

Energy release rates have been found to significantly increase with rising ICA. Furthermore, for the tested configurations, mode II energy release rates are higher than mode I values. An explicit tendency of the correlation between interface directions and energy release rates cannot be identified.

It is well known, that the structural energy dissipation capacity under extreme loading conditions is strongly related to the delamination behaviour of fibre reinforced composites. Therefore an application of the presented interface modification strategy is very promising to improve the crash and impact performance of load bearing components in automotive and aviation industry. Additionally, the possibility of a local adjustment of interlaminar properties enables additional degrees of design freedom, especially for multi-material components.

Acknowledgments

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