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Tearing and Delaminating of a Polymer Laminate

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Abstract

The fracture behaviour of laminated materials was studied in this work. The materials used in this work were low-density polyethylene (LDPE) laminated on polyethylene (PET). The thickness of the LDPE was 27 μm and the PET was 100 μm . Experiments were performed by using a 2-leg trousers specimen to analyse the tearing behaviour of the laminate in relation to the delamination. A clear delamination zone was observed during the crack propagation by tearing. Furthermore, a finite element calculation was performed to simulate the behavior around the crack tip during the tearing. A correlation between adhesion and crack propagation was discussed. Finally, the theory of Essential Work of Fracture (EWF) was used for predicting the specific total work of fracture along the tear path across the plastic zones.

Introduction

The purpose of this work was to study the fracture and tearing behaviors of laminated materials. The experimental analysis was performed on a tear-off (2-leg trousers-tear) specimen [1]. The same specimen geometry was used for all the tests. For a two-layer specimen with a pre-crack, load and extension were measured as well as for the individual layers of the laminate.

The issue of this work is to understand the fracture behaviour of packaging materials. The materials for food packages are often made of several layers to fulfil different requirements for the packages. Many of these packages have been designed to be simply opened by tearing through the use of a pre-crack. Different works related to tearing, fracture, delamination and properties of packaging materials have been done in recent years [2-7].

This paper shows the fundamental behaviour of the delamination during the tearing with a specially designed experimental set up by applying a tensile test machine and combined polarized optical photographs of the crack propagation tests. The finite element method together with the Essential Work of Fracture theory were also used to analyse the correlation between adhesion level, adhesion area and tearing force and the stress distribution around the crack tip. The influence of the delamination on the crack propagation from the out-of-plane mode (Mode-III) to the opening mode (Mode-I) is discussed.

Experimental methods

The Instron 5567 tensile test machine was used for performing the experiment. Grippers and load cell are mounted on the crossheads that can be moved accurately up and down by a digital control system. Pneumatic grippers with a 100 N load cell were used in the experiments. The accuracy of the measurement was 0.2% (0.2 N) [2]. The specimens were placed in the grippers with centre

marking to facilitate the position of the specimens correctly; the lower gripper was fixed while the upper gripper was moveable.

PET (polyethylene terephthalate) with the thickness of 0.1mm was extruded with a LDPE (low-density polyethylene) layer with 0.027 mm in thickness. Table 1 shows the mechanical properties of these two materials. These values are taken from early measurements [8] and are in good agreement with the standard values from the handbooks [9].

The specimens with a dimension of 30*35 mm were used. Note that an additional length of at least 70 mm was made in order to clamp correctly. The pre-crack was handmade with a knife and ruler in the centre of the specimen as shown in Fig. 1. All of the specimens were cut from the cross direction (CD) which is perpendicular to the machine direction (MD) during the production.

In order to observe the delamination and crack propagation phenomena, 5 specimens were prepared. The tensile test was stopped at 10 mm crack propagation for the first specimen, 20 mm for the second, 30 mm (3rd), 40 mm (4th) and finally 50 mm (5th). Load and displacement were recorded, see Fig. 2b. The specimens were then photographed as shown in Fig. 2a. To get more detailed information, more pictures were taken with a Leitz DMRXE optical microscope with a polarized lens as shown in the same figure.

Finally, tensile tests for the two single layers and their laminate were performed and the results of the load and extension are presented in Fig. 4.

Fig. 1. Geometry of the specimen (30 mm in width and 35 mm in pre crack length).

(a)

(b)

Fig. 2. (a) Load and displacement curves
(b). Photographs together with microscope pictures
of the 4 different specimens stopped at different displacements.

Essential Work of Fracture

The total work of fracture W_f in a pre-cracked specimen can be divided into two components, the essential fracture work W_e and the non-essential fracture work W_p in according with the *EFW* theory [10]:

$$W_f = W_e + W_p \quad (1)$$

When a specimen contains two laminated layers, the delamination work of fracture W_{delam} has to be introduced in addition to the essential and non-essential work of fracture.

The total work of fracture in a two-layers (a and b) laminate can then be written as:

$$W_{Tf} = W_{Te}^a + W_{Tp}^a + W_{Te}^b + W_{Tp}^b + W_{delam}^{a,b}. \quad (2)$$

Finite Element Analysis

Numerical simulations were carried out in FEM by using the commercial software ABAQUS [11]. The specimen was modelled as an assembly of two parts, each one representing the PET and LDPE layer. These two layers were connected to each other by a tie constraint. The geometrical dimensions for the model were based on the experimental specimen. The mesh for each part was constituted by continuum-shell elements of 8 nodes with reduced integration and a spider web mesh was obtained around the crack tip (see Fig. 3).

The material for each layer was considered as isotropic elastic-linear hardening plastic, without softening. The mechanical properties of LDPE and PET are shown in Table 1. The simulations were performed under static-general analysis and were supposed to reproduce a tearing test carried out at 50 mm/min.

Table 1. Material properties

Material	Thickness [mm]	Young Modulus E [MPa]	Poisson's ratio ν	Yield Stress σ_y [MPa]	Stress at break σ_b [MPa]	Strain at break ϵ_b
PET	0.1	1970	0.4	58.7	59	0.4
LDPE	0.027	221	0.4	12.5	14	0.8

Fig. 3 shows the von Mises stress distribution of each layer that was obtained from the simulations of a LDPE/PET laminate. It is observed that the plastic zone is not only located around the crack tip, but also extended to the legs of the trousers. Much higher stresses are obtained on the PET layer than on the LDPE layer, due to the material properties difference. The load-displacement curve obtained in the simulations is shown and compared well with the experimental ones in Fig. 4. When comparing the results in ABAQUS with and without delamination between the LDPE and the PET, the load level shows only a slight difference.

Fig. 3. FEM model in ABAQUS. Von Mises stress distribution on model of laminate PET/LDPE (layers shown separately).

Fig.4. Load vs displacement curve for several specimen's material.

Conclusions

1. Delamination occurs only at one of the tearing legs and always at the side (leg) where the LDPE layer is facing away from the crack tip.
2. During the tearing loading, the pre-made crack always starts to growth in the PET layer. The LDPE layer will be stretched and at a certain length, crack propagation in LDPE will follow.
3. After the delamination, as can be seen in Fig. 2(b), the plastic deformation in the LDPE layer is larger than in the PET layer. This is due to the later crack propagation in the LDPE and the phenomenon has also been found by FEM.
4. From Fig.4, it was found that the EWF needed to tear LDPE is much higher than the EWF to tear the PET layer (EWF is proportional to the area under the curve). This is due to the relatively low rigidity of LDPE compared to PET. In this case the large crack tip rotation in

the LDPE renders the local crack tip opening to become mode I, which has also been discussed in [12].

5. The EWF of the laminate is slightly lower than the sum of the EWF of the PET and of the LDPE separately although there is an additional EWF of lamination. This is because of the reduction of EWF in LDPE since it's extension is restricted by PET in the area where no delamination happened.
6. It can also be observed that the total EWF in LDPE is considerably larger than the EWF in the laminate. This is caused by the crack deflects in the laminate at an extension of about 70mm. This deflection of the crack will increase and lead to an earlier failure.

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