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Micro-mechanisms of a laminated packaging material during fracture

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ABSTRACT

The micro-mechanisms of fracture in a laminate composed of an aluminium foil and a polymer film are considered in this study. The laminates as well as the individual layers, with and without premade centre-cracks, were tensile tested. Visual inspection of the broken cross-sections shows that failure occurs through localised plasticity. This leads to a decreasing and eventually vanishing cross-section ahead of the crack tip for both the laminate and their single constituent layers. Experimental results are examined and analysed using a slip-line theory to derive the work of failure. An accurate prediction was made for the aluminium foil and for the laminate but not for the freestanding polymer film. The reason seems to be that the polymer material switches to non-localised plastic deformation with significant strain-hardening.

1. Introduction

A packaging material commonly consists of several material layers made of paperboard, polymers and aluminium foil. The aluminium foil (Al-foil) and the low-density polyethylene (LDPE) film are studied in this work. Paperboard together with these two materials are widely used as a material structure in aseptic food packages. The Al-foil is used as an efficient barrier towards exposure to oxygen and light in food packages. Furthermore, the Al-foil is usually combined with a ductile polymer layer to extend its durability. Additionally, paperboard layers are added to improve the mechanical strength of the full structure.

The final packaging material is exposed to different loading conditions during its lifetime: forming, folding, filling, distribution, storage, handling and finally opening, wasting and recycling by the consumer. Al-foil is not able to withstand as high local strains as the polymer film and the paper layers. Cracks initiated in the Al-foil can eventually spread into the polymer and the paper layers. Therefore, it is important to understand the individual fracture behaviour of the Al-foil and the LDPE layers and their roles as members of the laminated structure when designing opening devices.

In this work, the focus is solely on the Al-foil and the LDPE film. To be able to predict the damage evolution in the laminate, the fracture behaviour of the Al-foil and the LDPE are at first studied separately. Several studies of the fracture behaviour of the individual packaging material layers, for example paperboard, are presented in [1–4] and a metal film on a polymer substrate used in flexible electronics applications [5–7]. To form a well defined basis for the investigation of Al-foil and LDPE, centre-cracked panels exposed to in-plane uniaxial tensile mode I loading are further analysed in this

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Nomenclature

a	half crack length
h_A, h_L	initial thicknesses of Al-foil and LDPE
h_{cA}, h_{cL}	critical thicknesses of Al-foil and LDPE
m_A, m_L	extensional stiffnesses of Al-foil and LDPE
$t(\delta)$	actual specimen thicknesses for a single layer
t_A, t_L	current thicknesses of Al-foil and LDPE
x, y, z	coordinate directions
E_A, E_L	Young's moduli of Al-foil and LDPE
E_{Lam}	Young's modulus of the laminate
F	load per unit of length acting on the specimen
H	specimen's half height
J_f	work of failure
V	actual volume per unit length
V_0	initial volume per unit length
W	specimen's half width
δ	specimen extension
σ_{bA}, σ_{bL}	ultimate stresses of Al-foil and LDPE
σ_e	von Mises effective stress
σ_0	remotely applied stress
σ_c	critical stress at initiation of crack growth
σ_D	cohesive stress
σ_x, σ_y	stress in x and y-direction
σ_{YA}, σ_{YL}	yield stress of Al-foil and LDPE
ν_A, ν_L	Poisson's ratio of Al-foil and LDPE
ν_{Lam}	Poisson's ratio of the laminate
$\phi(a/W)$	finite width correction factor for the SIF
A	aluminium foil
L	LDPE
Al-foil	aluminium foil
LDPE	low density polyethylene

work. Adhesion between the different material layers has not been focused in this study. Therefore, the adhesion has been simplified and idealised. The bonds between the different layers are assigned similar strength as the induced traction forces created when the individual material layers contract due to stress localisation in the tensile tests, thus leading to separation of the two material layers locally. Delamination and the level of adhesion is an intriguing topic, cf. [5–8], and has to be included in future works.

As it was pointed out in [9], mechanical modelling of polymer materials is still in a rather early stage. A cell model has been so far developed and applied to investigate the effect of voids on matrix yielding and localised plastic deformation [10–12]. In the present work, a modified Dugdale model based on the slip-lines that were observed on specimen's cross-section was applied. This approach was utilised to study the localised plastic deformation of the single layer as well as the laminate. The fracture behaviour of the Al-foil and LDPE laminate has also been studied in previous work [13–15]. A frequent observation is the large variety of involved failure mechanisms in laminates of different compositions. Furthermore, crack tip fields for stationary and propagating cracks have been investigated. The crack tip fields and crack propagation as well as toughening mechanisms in a process zone of a laminate with a stationary crack tip have been investigated in [16].

It has been studied by [17] how the transition to necking can be delayed in polymer-metal laminates. The delay increases the energy-absorbing ability of the structure. The phenomenon is related to the ability of the elastic polymer to maintain a constant tension while the load carrying capability of the metal decreases with increasing deformation. The tendency of the strains to localise in the metal is obstructed by synchronised stretching of the polymer that resists localisation of the deformation. Strain in a periodic laminated structure may localise in regions with a width comparable to the individual layer thicknesses or alternatively in a larger region with a width comparable to the thickness of the entire laminate (cf. [18]). The study also suggests suitable combination of materials and layer thicknesses that will improve the structural toughness. The analysis suggests that a band of interacting co-necking layers for a tilted band across the laminate can arise during necking of several interacting individual layers.

1.1. Motivation, focus and aim

Opening devices have in recent years significantly increased in volume in the packaging industry. The failure process during the opening is intended, therefore the damage initiation and propagation of the process leading to complete fracture has