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An Experimental, Numerical and SEM study of Fracture in a thin polymer film

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Abstract: Observations and analysis of samples from scanning electron microscopic (SEM) micrographs has been concerned in this work. The samples originate from fractured mechanical mode I tensile testing of a thin polymer film made of polypropylene used in the packaging industry. Three different shapes of the crack; elliptical, circular and flat, were used to investigate the decrease in load carrying capacity. The fracture surfaces looked similar in all studied cases. Brittle-like material fracture process was observed both by SEM micrographs and the experimental mechanical results. A finite element model was created in Abaqus as a complementary tool to increase the understanding of the mechanical behaviour of the material. The numerical material models were calibrated and the results from the simulations were comparable to the experimental results.

1. Introduction

Fracture mechanical testing has significantly increased in packaging industry due to the emerging functionality and usage of opening devices in recent years. A better understanding of the mechanical and fracture mechanical behaviour of polymer films is needed. Experimental testing and analysis is a pre-requisite to determine the mechanical material properties i.e. stiffness, strength, ductility, plasticity and Poison's ratio used as input for the material models used in the numerical analysis.

Materials are strongest when stresses are evenly distributed over the entire test sample area. A reduction in the area and hence an introduced discontinuity caused by a crack results in the increase of stress localization [1]. The concentrated stress increases rapidly in a stiff material when the remotely applied load is increased; a crack start to propagate causing a fracture.

2. Experimental and numerical observations

A polymer film made of polypropylene (PP), with the thickness of 18µm, was studied experimentally. A sharp medical knife is used to cut the samples and to introduce the different cracks in the material. Three different geometrical shapes of the cracks were introduced in the centre of the specimens; flat, circular and elliptical all with $a=5mm$. These shapes were experimentally tested to understand the reduction in the strength, hence load carrying capacity, of the PP-material. Geometry of the specimens and the shapes are according to Fig. 1. The grip separation was initially $2H=230mm$ in the experimental and numerical test and the width of the specimen was $2W=95$. The lower end of the clamp is fixed and the upper clamp is moving at a constant displacement rate of *10 mm/min*. Packaging material was supplied by Tetra Pak in Lund and all the experimental testing was performed at the laboratory facilities in Blekinge Institute of Technology in Karlskrona. SEM pictures were created by cutting thin slices, 50 µm, of the fractured samples in a Microtome at Tetra Pak in Lund.

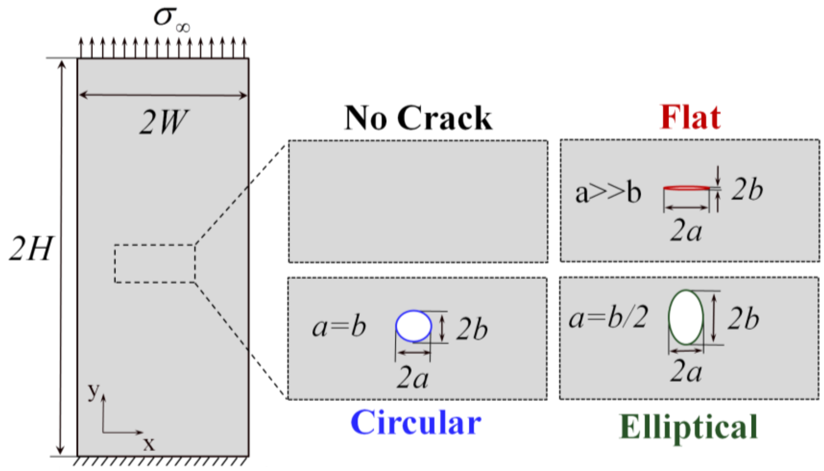

Figure 1. Test Specimen dimension and crack shapes

The mechanical behaviour of the continuum PP-film can be described by a Ramberg-Osgood material model and the associate material parameters are described in Table 1. This material model is simple to use and can easily be translated into numerical material model parameters.

Table 1. In-plane mechanical material properties for polypropylene (PP) film [2].

Material	Thickness [µm]	Young's modulus [MPa]	Yield strength [MPa]	Poisson's ratio [–]	Strain-hardening coeff. α	Strain-hardening exponent N
PP	18	5700	33	0.24	0.58	2.1

Experimental results show that PP is a relatively stiff and moderately extensible polymer film compared to other polymer materials. In Fig. 2, is mean values of force vs. extension plotted for five experimental tests for the three different crack shapes described in Fig. 1. Solid line represents the experimental test results and the dashed line represents the calibrated numerical results of the virtual tensile tests.

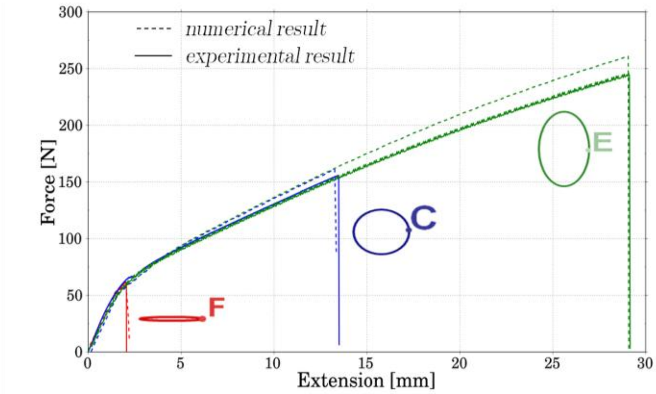

Figure 2. Fracture mechanical test results (mode I) showing force vs. extension for different crack shapes; F-Flat, C-Circular and E-Elliptical shape.

The observations from the experimental testing of PP are that the fracture process is brittle-like, rapid and unstable, in all loading conditions and the fracture surfaces looks similar in all four cases. During the tensile test is all stored strain energy dissipating and released when the crack propagates and new crack surfaces are created. The experimental results presented in Fig 2. are summarized in Table 2. The strength of PP becomes 93% with the introduction of elliptical crack while 57% strength in the material is observed in case of circular crack. Only 22% of the original strength is remaining in the PP-film when the flat crack is introduced in the centre of the specimen.

Table 2. Summary of experimental fracture mechanical results for PP-film.

Material	Thickness [μm]	Crack shape [-]	Tensile strength at break [N]	Tensile extension at break [mm]	Load carrying capacity [%]
PP	18	No Crack	280	37	100
		Elliptical (E)	261	28	93
		Circular (C)	160	13	57
		Flat (F)	62	2	22

The virtual tensile test model, created in the general finite-element software Abaqus 6.12, had a good agreement with the experimental results as shown in Fig. 2. Brittle micro cracking ahead of the propagating crack is the dominant phenomenon of fracture process in PP. The crack propagates through a craze at its tip for brittle materials, PP [3,4]. The discrepancy seen when introducing flat cracks with small widths, between theoretical strength derived by analytical expressions and the experimental observed fracture mechanical strength, described in Fig. 3, could be explained by the presence of very small micro cracks or micro flaws [5].

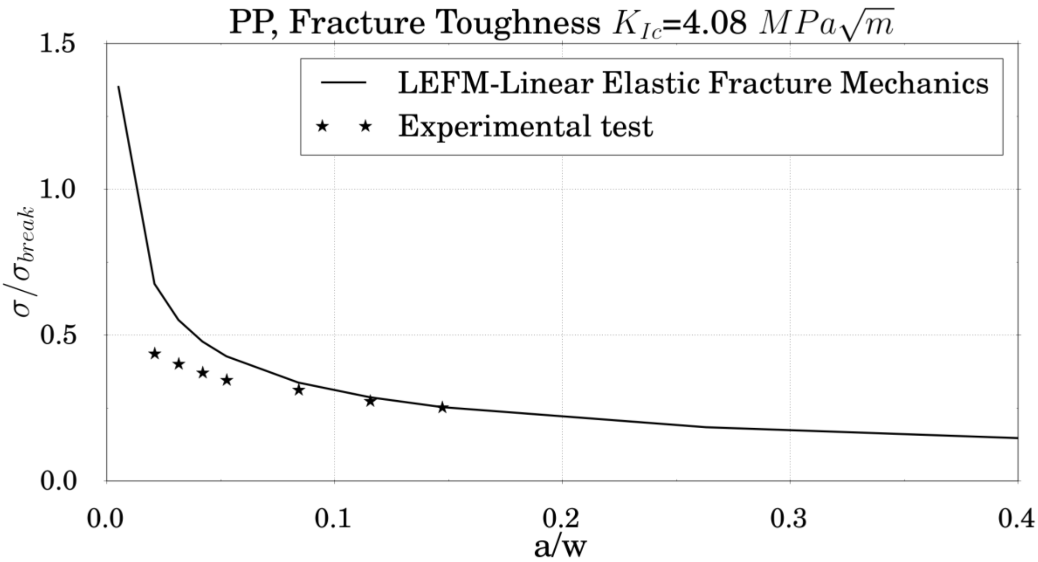

Figure 3. Normalized stress vs. crack length, PP 18μm [6].

The brittle fracture is pre-dominant in PP material where the mobility of the polymer is low and the specimen was in this study loaded perpendicular to the polymer orientation. The crack propagates nearly perpendicular to the loading direction *y* of the remotely applied stress, as shown in the SEM micrographs in Fig.4. The thickness of the PP-film is the z-direction illustrated in Fig. 4. Crack path is determined by the loading conditions and the material´s microstructure, in this case the combination of amorphous state and crystalline lamellas and how they are ordered and oriented.

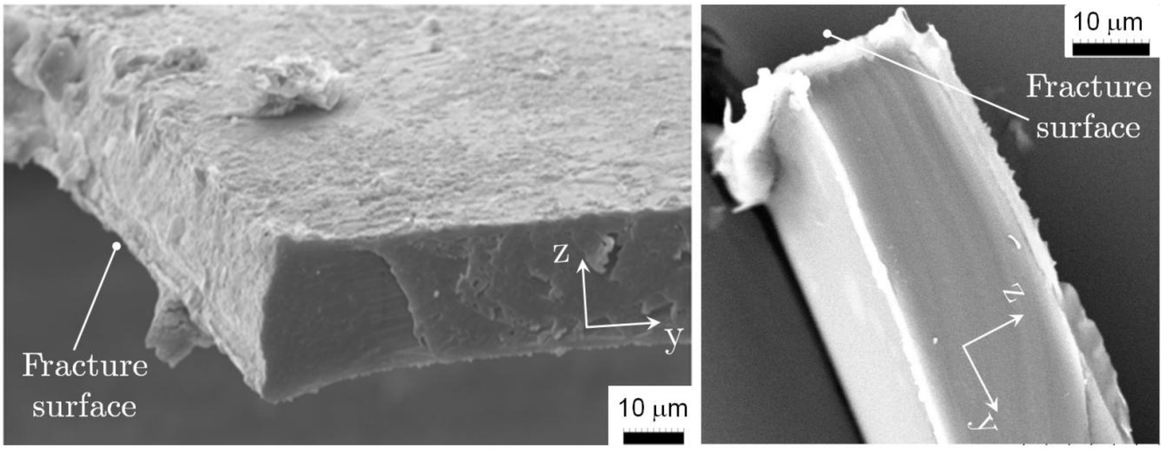

Figure 4. SEM of fracture surface of the PP-film exerted to mode I, uniaxial loading in y-dir.

4. Results

Polypropylene film used in packaging industry exhibits a rapid and brittle-like fracture process when exerted to in-plane mode I tensile loading. Instant and rapid crack growth is observed after the damage initiation. Load carrying capacity is reduced significantly, between 93% to 22%, depending on which of the three studied crack shapes that is introduced in the test sample. Fracture surfaces are created in all samples and propagated perpendicular to the principal stress direction with a negligible amount of plastic deformation and crack tip blunting. The continuation of the initial damage, the propagated fracture surfaces, look similar for all four cases, independent of initial crack shape, and were analysed with the aid of SEM micrographs. The fracture surfaces, almost perpendicular to the loading direction, exhibits no thinning in the thickness direction in the localized strain region. Comparable results were achieved with a FEM model and this can be used further on with reliable predictions.

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