Trouser tear tests of two thin polymer films

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Abstract Trouser tear testing has been concerned in this research work. A polypropylene film and a low density polyethylene film used in the packaging industry are considered. The experimental trouser tear tests showed different results for both materials when they were subjected to load in different material directions. Therefore the hypothesis was verified, that the in-plane material orientation/alignment induced during manufacturing, hence creating anisotropic in-plane mechanical properties, also affects the tearing behavior. A brittle-like failure was shown in the polypropylene film while the low density polyethylene presented a highly ductile behavior. The two polymer films can be classified as one low-extensible and one high-extensible material according to the test method utilized. Material parameters in the principal material directions i.e. manufacturing direction and cross direction were extracted from the experimental tests for further numerical studies. Scanning electron microscope was used for micromechanical and fractographical analysis of the crack tip and crack surfaces created during the tests. The methods discussed will help classify different groups of materials and can be used as a predictive tool for the crack initiation and crack propagation path in packaging material, especially thin polymer films.

Keywords Anisotropic, thin polymer film, crack propagation, fracture mechanics, SEM

1. Introduction

Polymer films are extensively used in food packaging industry due to their beneficial mechanical properties, i.e. the combination of stiffness, strength and ductility. During transportation, handling and usage of packages, polymer films are exerted to different loading conditions. Polymers and rubber-like materials have previously been extensively studied experimentally in various fracture modes [1-3]. For the case of tearing, the experimental and theoretical analysis has been performed in [4-8]. This work will focus and extend the analysis on the experimental trouser tear tests in three different material directions for two types of polymer films used in packaging industry.

Fracture properties related to the specific material parameters such as critical fracture toughness, energy release rate, fracture energy and crack propagation resistance can be determined using a fracture mechanical test method. In brittle material this procedure is well known but for ductile material it is less developed. The two important fracture modes involved in the trouser tear test, mode I – in-plane opening mode and mode III – anti-plane shearing mode together with the mixed mode - trouser tear test are depicted in Fig. 1.

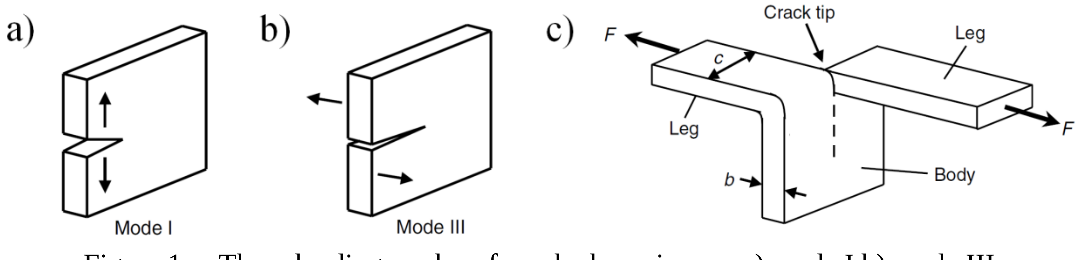

Figure 1. Three loading modes of cracked specimens: a) mode I b) mode III and c) mixed mode trouser tear test [9]

2. Materials

Two types of polymer films with different mechanical behavior were tested and analyzed in this work. One oriented polypropylene (PP) film and one low density polyethylene (LDPE) film were experimentally tested. The mechanical in-plane material properties for these two thin packaging materials have thoroughly been examined in previous works with slightly different scopes and interests [6-7,10-13]. In-plane elastic anisotropic material behavior is shown in the PP film according to (Table 1). To be able to distinguish the principal material directions a naming convention is used i.e. manufacturing direction (MD), cross direction (CD), and 45 degrees to the manufacturing direction (45). These abbreviations are further on used to indicate in which direction the load has been applied. In-plane material properties for the PP and LDPE are presented in (Table 1). In-plane material properties primarily dominate the mechanical behavior in the two polymer films studied. This is due to the thin thickness of the polymer films, hence plane stress assumption is valid. Therefore, out of plane properties are disregarded in this work.

Table 1. In-plane mechanical material properties for thin polymer films [10], [13]

Material	Thickness [μm]	Material orientation [-]	Young's modulus [MPa]	Yield strength [MPa]	Poisson's ratio [–]
PP	18	CD	5100	29	0.43
		MD	2200	28	0.25
		45	2800	28	0.30
LDPE	27	CD	140	5.1	0.4
		MD	140	5.1	0.4
		45	140	5.1	0.4

Manufacturing of polymer films involves several processing steps. During these different steps, polymer chains are aligned or enforced to orient in the manufacturing/rolling direction (MD) or stretching direction (MD or CD). The degree of orientation in the polymer chains vary in different polymer types and mixture of polymers. Temperature, thickness, chemical structure, polymer chain lengths, number of cross-links, entanglements and rate of crystallinity are all parameters affecting the final mechanical properties in the material. Anisotropy, different mechanical behavior in different directions, is therefore most often the case for many polymers. Due to anisotropy, polymer films tend to follow different preferred crack directions and find the lowest resistance path for crack propagation. Initial direction of crack extension depends of loading scheme and type of material. Brittle materials, as PP in this study, usually fracture by mode III defined in Fig. 1. Ductile materials, as LDPE in this study, usually fracture by mode I and mode III defined in Fig. 1 when exerted to a trouser tear test. If a crack is introduced into a specimen, such as in the trouser tear test, the stress distribution is no longer constant and homogenous within the material. The stress will vary and this variation is due to size and shape of crack and geometry of specimen. In fact, the geometry and the type of loading also have a significant influence on the crack propagation behavior. In brittle materials the process zone will be very local and in the vicinity of the crack tip, all the energy dissipates and new crack surfaces are created. On the other hand in a ductile material where a lot of plastic deformation occurs the process zone and active zone is a rather large area surrounding the crack tip. In this case a lot of energy is consumed in the plastic flow and for the trouser tear test in substantial leg deformation.

3. Experimental Procedure

Preparation and cutting of specimens were performed after pre-conditioning of the materials at 23°C and 50% RH for 40 hours prior to test in accordance with the test procedure defined in the standard ASTM D618-08 [16]. Sample cutting of the two types of polymer films were done with a sharp medical knife and it is recommended to frequently change blades. To minimize uncontrolled errors, such as edge effects, the specimens were cut in the same way every time with the same operator. Mounting and handling of the polymer film was carefully done in order to not damage the material and edges. Trouser tear test specimen geometry and dimensions are shown in Fig. 2. When the specimen is mounted in the tensile test equipment it looks like a pair of trousers, which explains the name of the test method. The 'legs' of the trouser specimen are then pulled in opposite directions to create tearing action. One of the grips in the tensile test machine, holding the specimen, is fixed and the other one is moved at a constant rate (10mm/min) during the test. Specimen extension is measured by grip separation. The test method utilized in this work, the American standard ASTM 1938-08 [15], was used for calculation of the tear resistance and is similar to the European standard ISO 6383-1:1983 [17]. These two methods calculate the force necessary to propagate a crack in a trouser tear test in plastic/polymer films with a thickness less than 250 μm. Several experimental tests, minimum five for each material direction, were performed for each test setup to characterize the mechanical behavior of each material and for different material orientations.

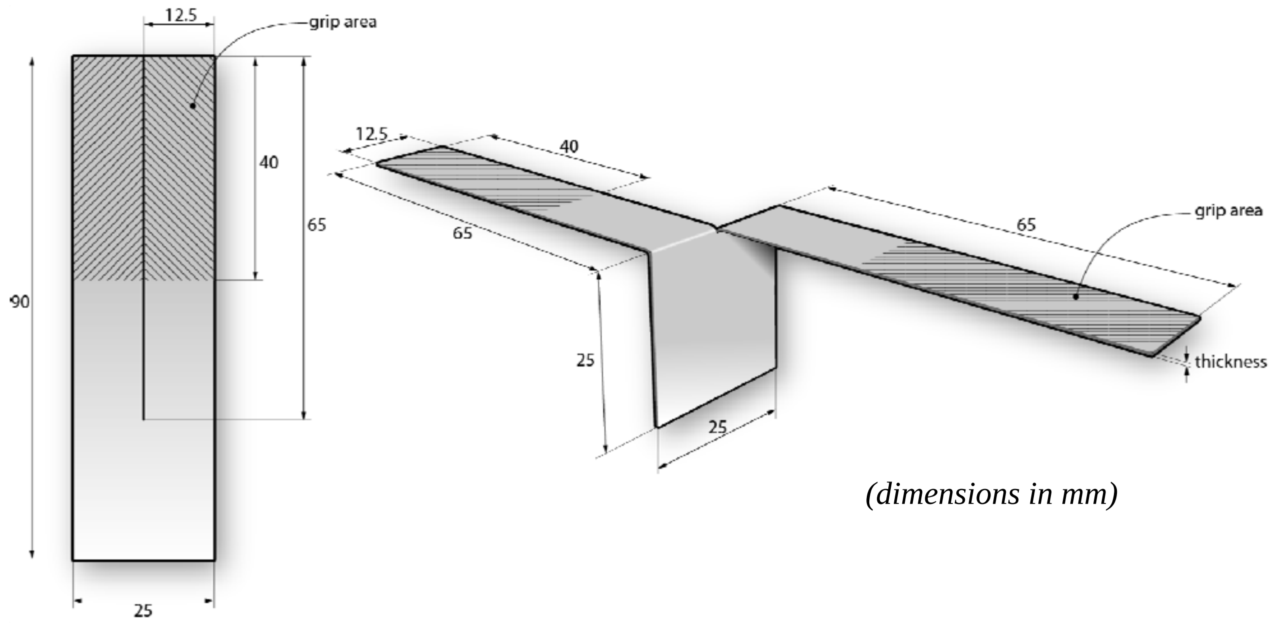

Figure 2. Trouser tear test specimen geometry, illustration by Carl Nordenskjöld

According to Fig. 2 a pre-made crack is introduced in each specimen before mounting in the experimental equipment. During the test, when the legs are separated and thus extended, the pre-made crack will continue to grow. In the figure the grip area is marked (hatched) and the one-color area is the material subjected to load, where the tearing action takes place. PP is brittle and sensitive to stress and to avoid crack initiation prior to the test a small slack (2 mm) was introduced when mounting. The registered forces in the experimental tests are low and therefore it is important that the grippers are rigid and unable to move during the tests. Even a small vibration can cause significant deviation in results and this external noise has to be controlled and minimized. Hence the gripping equipment was adjusted to be ultimately stiff to prohibit any movement of the clamps in the other directions than the stretching direction.

4. Experimental trouser tear testing results

In the test method, ASTM D1938-08, [15] two different types of behavior is classified; in this study PP is a low extensible or non-extensible film and LDPE is a highly extensible film. The generic response graphs from trouser tear tests, for the two different classes of materials are displayed in Fig. 3. Low extensible films, i.e. PP, exhibit a constant load during trouser testing. For highly extensible films, i.e. LDPE, the deformation energy of the specimen legs is significantly higher than the tearing energy. Tearing of highly extensible films is accompanied by significant plastic deformation.

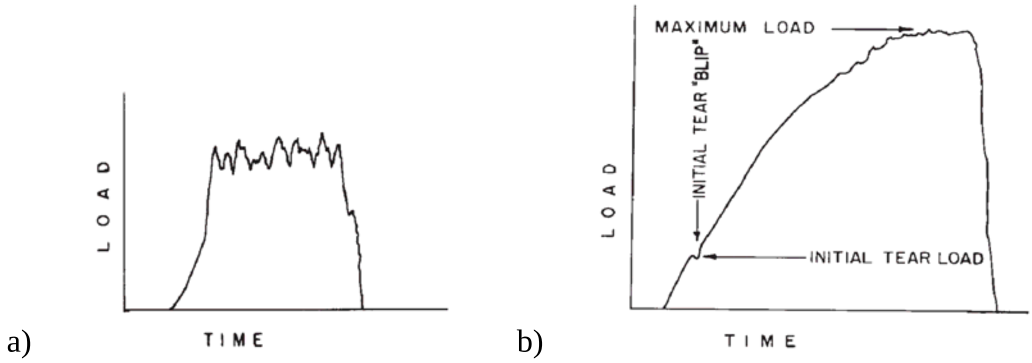

Figure 3. Load vs. time for trouser tear tests in a) low-extensible and b) highly-extensible polymer film, [15]

The force needed to propagate the pre-made crack in a polymer film specimen was experimentally measured in the laboratory at Tetra Pak in Lund. The utilized test method can be used for rating the tear propagation resistance of various plastic/polymer films of comparable thickness. Force and extension were recorded during loading and tearing of the specimens. The results are shown in Fig.4 for PP and in Fig.5 for LDPE. Five different specimens for each direction were studied to get an idea of mechanical behavior and statistical variation in the two types of polymer films. The force registered in the PP-film, as shown in Fig. 4, was low (note the unit mN on the y-axis). There was a significant difference of registered force in all the three material directions.

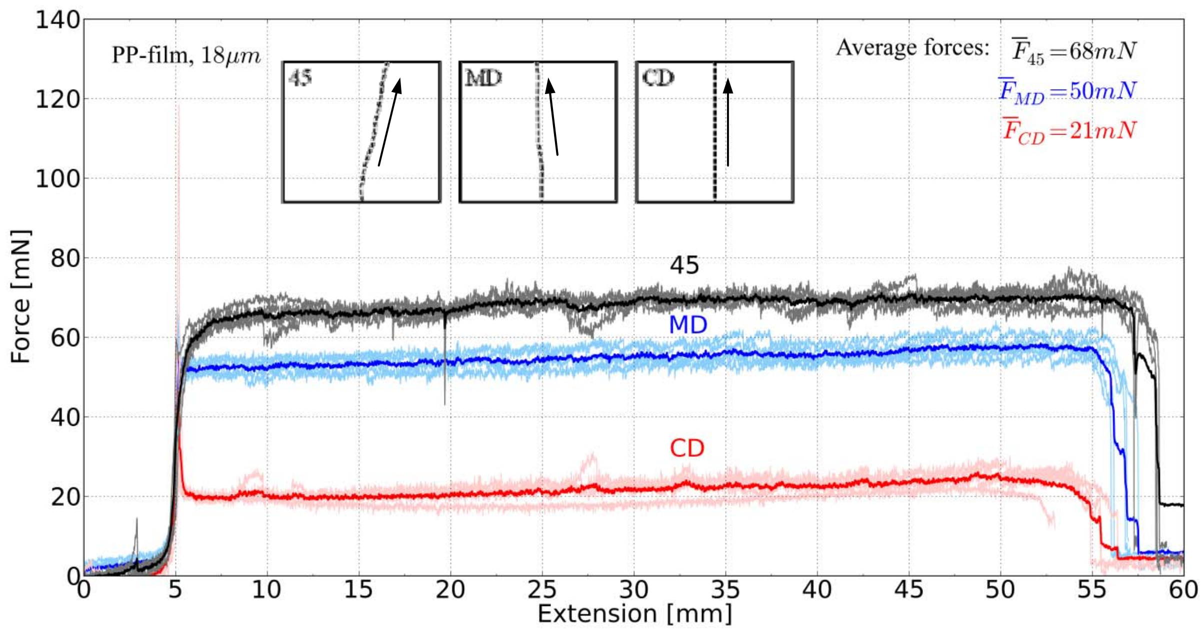

Figure 4. Trouser tear test in material direction 45°, MD and CD for PP-film, force vs. extension.
Bold lines represent mean curves for each material direction.

For PP it is possible to clearly distinguish the three different material orientations as shown in Fig. 4. A noticeable high peak is shown in the PP-CD samples which probably indicates the breakage of chemical bonds in-between the polymer chains or the crystallites. The force is significantly higher than the average force for the continuous crack propagation when the material has found the lowest energy crack path direction. Lowest tearing resistance path for PP-45 is along the material alignment in CD, therefore the crack path is not orthogonal to the stretching direction. This means that the highest force is registered in these specimens. The experimental trouser tear test results for PP is depicted in Appendix A at different loading stages. In Appendix A is the three different crack propagation paths noticeable as depicted above in Fig. 4. It is important to note that the small fluctuations in the force values during tearing, present in all PP-graphs in Fig. 4, are not noise from the experimental equipment but rather due to the “stick-slip” behavior observed during fracture in many polymers [8]. The frequency and amplitude of these small fluctuations most probably relates to the morphology and micro mechanism of the polymer material, such as the polymer chain alignment, arrangement of crystallites, and distribution of crystalline and amorphous phases. However, systematic micro structural and fractographical characterization is needed to fully understand the “stick-slip” behavior. The LDPE-specimens don’t show these small fluctuations in the force values during tests as shown in Fig. 5. The experimental trouser tear test results for LDPE is depicted in Appendix B at different loading stages.

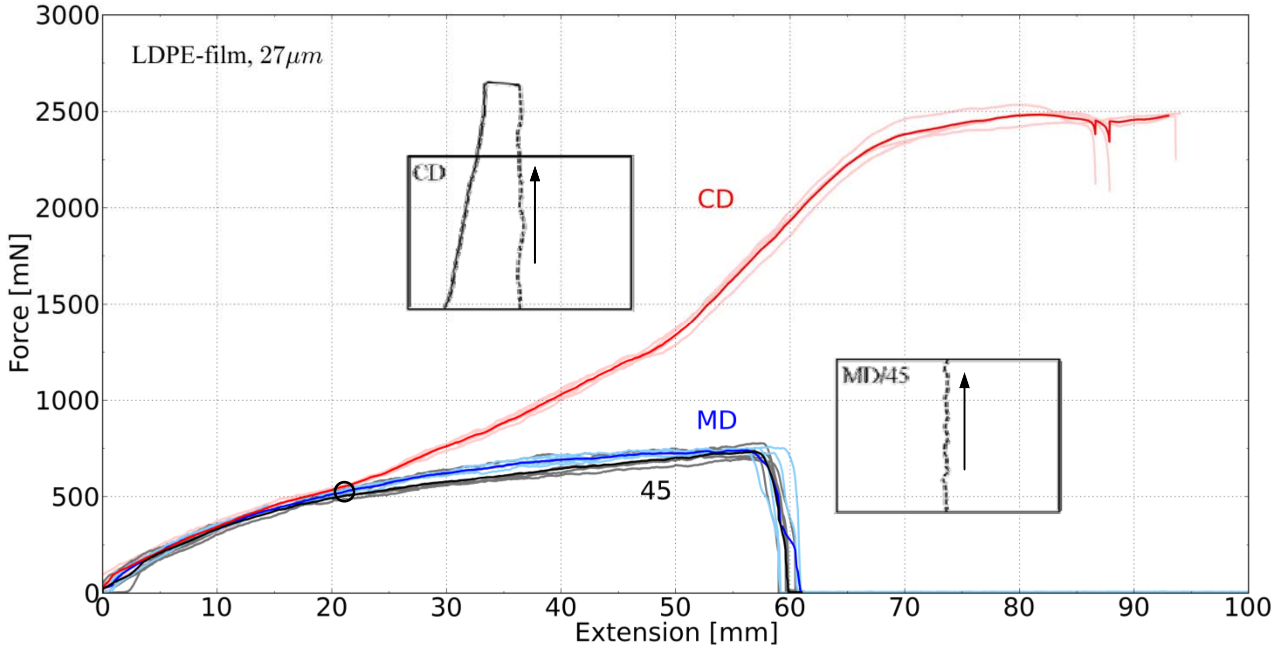

Figure 5. Trouser tear test in material direction CD, MD and 45° for LDPE-film.
Bold lines represent mean curves for each material direction.

For LDPE the total extension of the trouser test is 90 mm in CD and 60 mm in MD and 45. The total extension from tearing is only 50 mm, hence a significant part of the LDPE extension is elongation of the two legs. The un-bundled polymer chains, with the majority oriented in MD, enable a significant stretching in CD. Therefore a lot of energy is dissipated in material rearrangement, plastic work, elongation of the legs and heat generation. However, the initial part, until the circle shown in Fig. 5, similar behavior is presented in all three material directions CD, MD and 45 in LDPE. For low extensible films such as PP on the contrary, there is no deformation of the legs and the total extension is therefore 50 mm, the same length as the minimum possible tearing distance. Test results for highly extensible films, i.e. LDPE is depicted visually in Appendix B, and for low extensible films, i.e. PP in Appendix A.

In addition to the well known fracture mechanical parameters, such as stress intensity factor and J-integral defined in [14], Rivlin and Thomas defined the critical fracture energy from a trouser tear test. This quantity is also known as tearing energy, which is the energy spent per unit thickness per unit increase in crack length. Tearing energy includes surface energy, energy dissipated in plastic flow processes, and energy dissipated irreversibly in viscoelastic processes [1]. The equations described below are derived from the trouser tear test based on theoretical analysis of crack growth behavior [5]. This can simplify the description of the tearing energy from the experimental results. The equation for calculation of tearing energy was derived with experimental test of rubber-like materials and is also applicable for polymers. The tear strength equation to calculate the critical tear energy, T_C, of a propagated crack in LDPE in this study is

$$T_C = \frac{2F\lambda}{t} - wE \quad (1)$$

F is the tear propagation force, w is the initial width of specimen, t is the thickness of specimen, E is the strain energy density. For LDPE the strain energy density can be calculated using the area under stress-strain curve from an ordinary tensile test. It was found that the strain energy for LDPE is, $E_{LDPE} = 2.8\ N/m^2$. λ is the extension ratio of the legs, current length of specimen divided by initial length, which is normally 1 except for some materials which have high extension of legs as LDPE-CD ($\lambda = 1.8$). In case where high stretching of legs is visible, then Eq. 1 will be used to calculate the critical tear energy. Strain energy density, E, becomes zero in materials with no leg extension, in this study for PP, resulting in the general equation used widely for calculation of critical tearing energy in brittle materials,

$$T_C = \frac{2F}{t} \quad (2)$$

The relationship between rate of tearing and strain energy release rate is a material characteristic that is independent of test specimen geometry, when tested low extensible materials [4]. The extension in the specimen legs is negligible and ignored for such cases. It can be confirmed from Eq. 2 that the critical tearing energy is independent of the initial sample geometry and crack length. This assumption is valid only if the specimen undergoes mode III dominated failure. Critical tear energy for the PP & LDPE is calculated using the above equation. Crack propagation for PP is a completely mode III phenomenon so its crack propagation is a complete tearing process, while LDPE has plastic flow and deformation of legs in addition to tearing which is generating a mixed mode I and mode III failure. Tearing or crack propagation force, tearing work, tearing energy & tear extension for PP and LDPE are summarized in (Table 2).

Table 2. Trouser tear test results for two thin polymer films; PP and LDPE

Material	Thickness [μm]	Material orientation [-]	Tearing Force [mN]	Critical Tearing energy [N/m]
PP	18	CD	21	2330
		MD	50	5560
		45	68	7560
LDPE	27	CD	2500	333330
		MD	750	55560
		45	750	55560

The force applied in a trouser tear test for PP and LDPE is plotted versus extension of the clamps in Fig. 6. Both loading and un-loading is presented in the graphs. Arrow 1 indicates the initial extension to start a tear, overcome the threshold value of force needed to start the pre-made crack growing, point F indicates the initial force required to start a crack (crack-initiation), arrow 2 indicates the force needed to propagate the crack which is constant for PP and increasingly non-linear for LDPE. Arrow 3 indicates the final retraction of specimen as applied force is removed. Area below arrow 1 indicates the strain energy stored in specimen before crack growth (energy required to start a crack), area below arrow 2 indicates the energy released during crack extension Arrow 3 indicates the stored energy in the legs at the end of test. The non-linear segments of the curves, prior to tearing and during unloading, correspond to stored strain energy in the legs of the specimen.

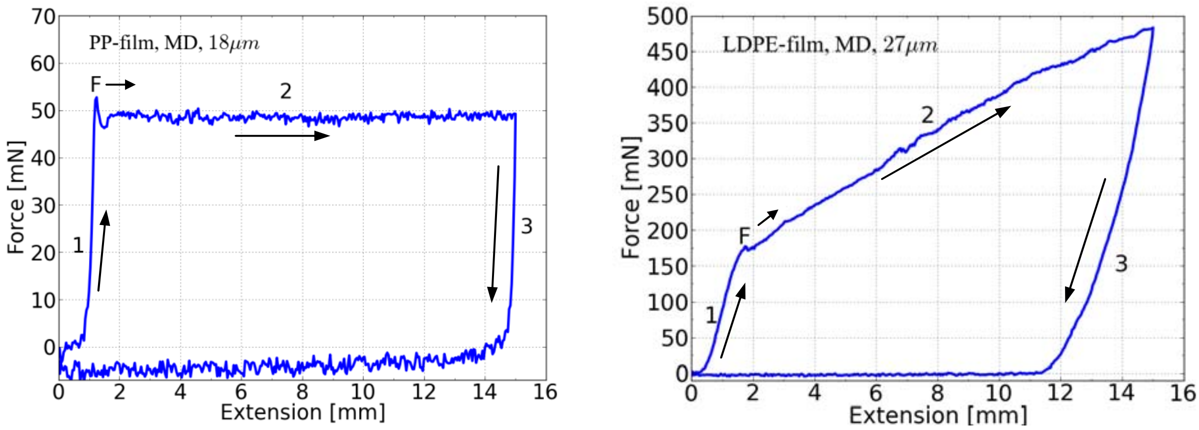

Figure 6. Trouser tear test, loading and unloading for PP and LDPE-film in MD.

From the fracture surfaces shown in Fig. 7 for PP and LDPE it is evident that the fracture mechanical behavior and processes are different in the two materials. Substantial plastic deformation is developed in the LDPE material leading to localized thinning of the cross section. PP material has no plastic deformation in the crack tip for tearing fracture. Fracture edges are presenting a wavy shaped geometry in the LDPE and representing a straight line in PP. This is an area that needs more thorough understanding and knowledge for future studies. The mechanical behavior and also the fracture mechanical behavior are strongly coupled to the manufacturing technology and process settings, what polymers that are used and also the morphology and chemical composition. This subject has to be addressed separately and finding technologies to be able to increase the knowledge and understanding of the micro mechanical behavior is important.

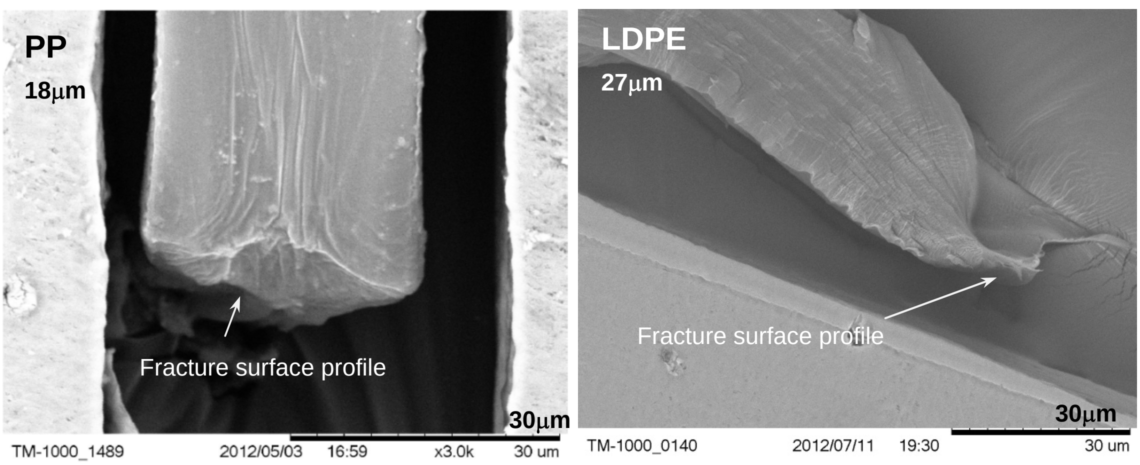

Figure 7. SEM pictures of the fracture surface profile in PP and LDPE.

5. Conclusions and discussion

Experimental trouser tear tests were performed in this research work according to the American standard ASTM 1938-08 [15]. Two polymer films with different fracture mechanisms and micro structural composition were studied, PP and LDPE. Repeatable and reproducible experimental results were obtained after adjustments of the experimental equipment. Non-compliant test equipment was used due to the low forces registered in the tests. For both materials different responses were measured in the three material directions MD, CD and 45.

Trouser tear test results for the highly extensible polymer film, LDPE in this study, show:
- Fracture is governed by a mixed mode material behavior (mode I and mode III).
- The tearing energy is directly proportional to the deformation of the plastic yielded zone at the fracture edge, hence creating increasing deformation zone with increasing force. Thus deformation and strain energy rate is continuously increasing showing higher tearing energy.
- One of the legs elongates when the crack tip exhibit both mode I and mode III failure, which is clearly shown in the case of loading in CD material direction.

Trouser tear test results for the low extensible polymer film, PP in this study, show:
- Fracture is solely governed by mode III material behavior.
- There is no pronounced yielded zone, hence all strain energy is consumed and dissipated into local plastic flow, crack tip growth, polymer chain orientation and heat generation.
- Low covalent bonding forces and voids present in the material gives a knotty or shaky tear graph. Knotty tear is due to that the crack path follows these small voids which result in small variation in forces.

It was found that, the low-extensible PP film requires only a small force to fracture, almost negligible compare to the highly-extensible film, LDPE. If the material fractures in a brittle fashion, PP in this case, the result is independent of the shape of the test specimen and the manner in which the deformation is applied. An almost constant tearing force is needed in brittle materials to propagate the crack in different material directions. In this type of material the local deformation in the surroundings of the crack tip is determining the global response. However, if the material is ductile the behavior is much more complicated. The plastic flow at the crack tip is not directly involved in the fracture process and hence the deformation doesn't only take place locally in the vicinity of the crack tip. The test specimen size and geometry influence the result and therefore it is hard to find a material parameter governing ductile tearing. To separate the leg extension, the plastic flow and the actual tearing force is therefore challenging. It should be noticed that tearing force is also influenced to a large extent by type of polymer, temperature, material anisotropy and loading rate which has not been tested/discussed in this work. Finally, as seen in the SEM pictures, it is possible to distinguish a low-extensible and a highly extensible material by studying at the fracture surfaces in samples. In the highly extensible material the fractured surface is presenting a wave-shaped geometry. Low-extensible material shows a very sharp crack surface and hence a straight line is created during the trouser tear tests.

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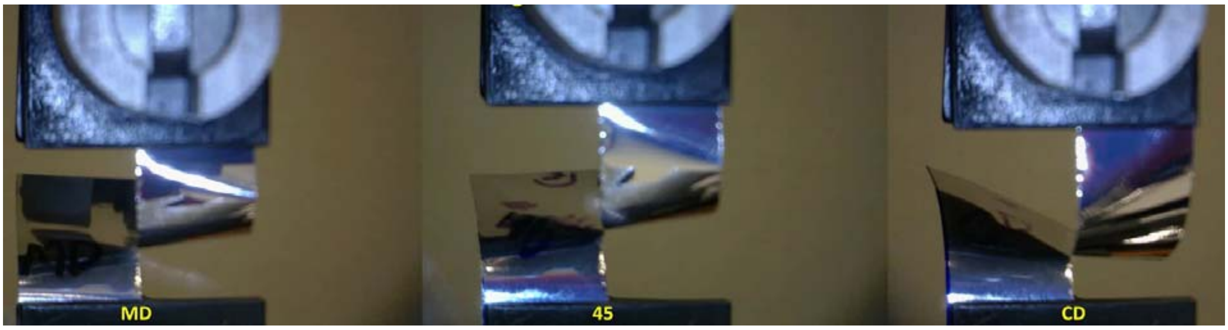
Appendix A – *Polypropylene (PP) during trouser tear test,* ASTM D1938-02

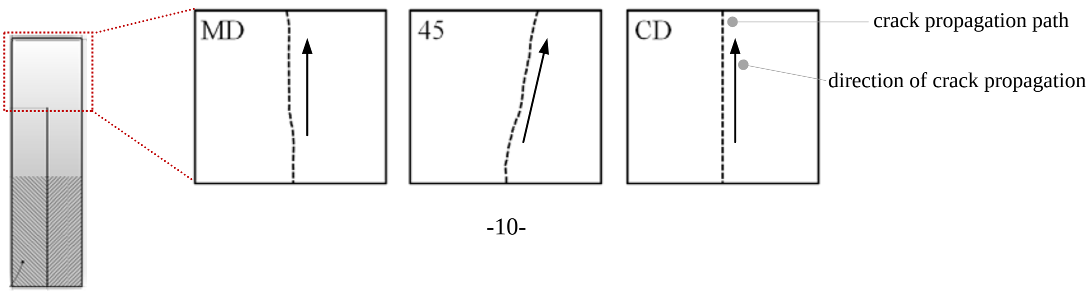
a) initial trouser tearing



b) continuous trouser tearing

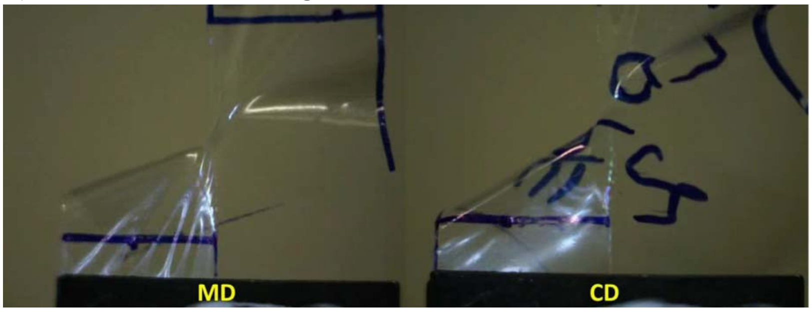
c) final trouser tearing, edge effects may come into consideration

d) finalized trouser tear test



Appendix B *– Low density polyethylene (LDPE) during trouser tear test,* ASTM D1938-08

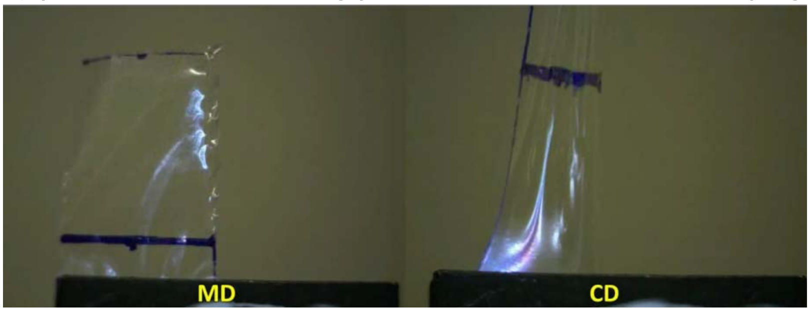
a) initial trouser tearing



b) continuous trouser tearing

c) final trouser tearing for MD (edge effects), extension of legs in CD

d) finalized trouser tearing for MD, continued extension of legs in CD



e) finalized trouser tear test for MD, continued extension of legs in CD