Fracture Mechanical Trouser Tear Testing in Thin Polymer Films
(Experiments Along with Numerical simulations)

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Thesis submitted for completion of Master of Science in Mechanical Engineering with emphasis on Structural Mechanics at the Department of Mechanical Engineering, Blekinge Institute of Technology, Karlskrona, Sweden.

Abstract:
Tensile and Trouser tear tests of thin packaging polymer films have been done successfully in this research thesis. Two different polymers (PP and LDPE) are used. Mode I and Mode III fracture tests have been used for crack propagation analysis. Several experiments are performed to calculate the material parameters. The research study includes the experimental test along with virtual tests using the FEM software Abaqus 6.12-1. ASTM standard 1938-08 is followed for specimen size and experiments are performed on Instron 5655 with 100 N load cell, Tetra Pak Package Lab at Lund. Repeatable and reproducible results are obtained for the principle directions (MD, CD and 45) for Tensile and Trouser Test for brittle and ductile film. Experimental and Numerical Tensile tests have been performed and validated on different crack shapes using MTS machine, BTH Material lab. Visual analysis is made using the Scanning Electron Microscope and polarized light microscope to analyze material and crack propagation behavior. Tearing force for crack propagation is extremely small compared to the Tensile tests. A detailed Essential Work of Fracture (EWF) study has also been made to further understand the behavior. The work will provide an aid to simulate the working conditions better to have a detailed understanding of the polymer behavior.

Key Words: PP, Mode I, Mode III, Tensile test, ABAQUS simulation, Crack shapes, Tearing behavior, EWF, Polarized light, SEM microscope.
Acknowledgements

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Karlskrona, August 2012

Nasir Mehmood
Tan Mao
Gaurav Bhupati
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Notation

\begin{align*}
A & \quad \text{Area} & [m^2] \\
D & \quad \text{Displacement} & [m] \\
E & \quad \text{Young’s modulus} & [MPa] \\
\varepsilon & \quad \text{Strain} & \\
F & \quad \text{Tensile force} & [N] \\
G & \quad \text{Energy release rate} & [J/m^2] \\
H & \quad \text{Height} & [m] \\
K_{IC} & \quad \text{Fracture toughness} & [MPa\sqrt{m}] \\
K_I & \quad \text{Stress intensity factor for mode I} & [MPa\sqrt{m}] \\
K_{III} & \quad \text{Stress intensity factor for mode III} & [MPa\sqrt{m}] \\
l & \quad \text{Ligament length} & [mm] \\
\sigma & \quad \text{Stress} & [MPa] \\
P & \quad \text{Tearing Load} & [N] \\
T & \quad \text{Specimen thickness} & [m] \\
\tau & \quad \text{Shear stress} & [MPa] \\
\nu & \quad \text{Poisson’s ratio} & \\
W_e & \quad \text{Essential work of fracture in plastic zone} & [J] \\
W_F & \quad \text{Total work of fracture} & [J]
\end{align*}
## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ASTM</td>
<td>American society for testing and materials</td>
</tr>
<tr>
<td>CD</td>
<td>Cross direction</td>
</tr>
<tr>
<td>C-T</td>
<td>Crack tip</td>
</tr>
<tr>
<td>CTOD</td>
<td>Crack tip opening displacement</td>
</tr>
<tr>
<td>DENT</td>
<td>Double edge notch tension</td>
</tr>
<tr>
<td>EPFM</td>
<td>Elastic plastic Fracture Mechanics</td>
</tr>
<tr>
<td>ESIS</td>
<td>European Structural Integrity society</td>
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<tr>
<td>EWF</td>
<td>Essential work of fracture</td>
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<tr>
<td>FEM</td>
<td>Finite element method</td>
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<tr>
<td>ISO</td>
<td>Organization for international standards</td>
</tr>
<tr>
<td>MD</td>
<td>Machine Direction</td>
</tr>
<tr>
<td>MSYM</td>
<td>Modified strip yield model</td>
</tr>
<tr>
<td>MTS</td>
<td>Mechanical Testing and Simulation</td>
</tr>
<tr>
<td>NLFM</td>
<td>Non-Linear fracture tension</td>
</tr>
<tr>
<td>P.C.T</td>
<td>Pre crack tip</td>
</tr>
<tr>
<td>PP</td>
<td>Polypropylene</td>
</tr>
<tr>
<td>SI</td>
<td>Standard international</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning electron microscope</td>
</tr>
<tr>
<td>SLR</td>
<td>Systematic Literature Review</td>
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</table>
1. Introduction

1.1 Background

Thin polymer films are finding increasing interest in biological sciences and semiconductor packaging, along with their popular application as packaging material. Mechanical stresses and fracture behaviour is also very interesting for packaging material producers like Tetra Pak. Tetra Pak is one the world’s leading food processing, package materials and packaging solution provider. Every year Tetra Pak is providing new and innovative package designs and package opening solutions to make the end customer’s life as easy as possible. Now after 60 years Tetra Pak is available in 170 countries of the world with 66 003 processing units in operation. Tetra Pak has 11 R & D that are constantly finding new food processing and package opening solutions [1].

In industrial application, these film material need to experience so many mechanical stresses during handling and usage. Most of these films are durable for tensile stresses while prone to failure upon tearing. So, it’s quite important to know its critical energy release rate during fracture and fracture behaviour for a accurate material design approach.

More and more research is going on to develop and find new packaging and opening solutions in the process development centres of the company. New materials are also being tested to further improve the package characteristics. Recently new opening caps are developed as shown in Figure 1.1. The commercially available materials are tested under different loading scenarios to see the behaviour of the new materials usually polymer films or sheets. Several tests like uniaxial tensile tests, shearing test, Trouser tear test, bending tests, compression tests, creep tests and several other physical test could be perform for material analysis.
1.2 Objective

Uniaxial Tensile and trouser tear tests are focused in this work. In this research thesis oriented Polypropylene and low density poly ethylene are selected for physical testing to investigate its material properties and to find out its crack propagation behavior. These tests are performed at Tetra Pak package laboratory in Lund.

The oriented Polyproplyne test specimens are modeled and tested in Abaqus 6.12-1, which is Finite element analysis software known for its high quality and performance for the challenging tasks. The extracted material data is used in Abaqus, to perform the virtual tests for the same material to look and compare the physical results. The virtual tests have their own significance and can be used in a good way to reduce the amount of needed physical tests. The virtual test method could be quite simple, economical and will shorten the time gap for the new product development process. Polymer films are usually tested for anisotropy (material properties variation). The anisotropic material data from these physical tests is extracted to perform the real time simulations in Abaqus. Virtual model can be improved to get a close match between the physical and virtual results.

Systematic literature review is performed for the trouser tear testing. Fracture mechanics knowledge is used for different crack shape and crack propagation tests. The thesis is done to provide and develop the knowledge of oriented polymer films. The physical and virtual test method
development was the essential part of the thesis work. Several test methods used that will provide the best available solution and also the material model for realistic and complex simulations in the company. Polymer material behavior and the induced stresses in the structures are the main focus of all these tests. There is also an extension to the previous knowledge that has been gained in the recent months.

1.3 Research Questions:

1) How crack propagates in Mode III for thin polymer films? How experimental and numerical Trouser Tear Testing should be performed?
2) Crack propagation behaviour for low extensible and highly extensible materials? Mode I or Mode III? Mix Mode crack growth? Fracture Crack growth in different Crack Shapes?
3) Material Model development for Mode III using FEM analysis software Abaqus.

1.4 Research Methodology

Using idealization, theoretical data will be searched and acquired, then compared to the experimental data. Using experimental data numerical or virtual testing will be performed and numerical results will be calibrated and compared to the experimental results. Finally, on the basis of these comparisons, it will be determined if the idealizations and method of predictions are, in fact, accurate and valid. The steps and method is depicted in Figure 1.2.
Figure 1.2 Research Methodology using Systematic Literature review (SLR)

Standard methods like ASTM 1938-08, ISO-6383-1, and ESIS etc. are found useful for trouser tear tests and uniaxial tensile tests. Python (which is a programming language which work quickly and integrate system more effectively[5]) is used to plot the physical test and virtual Test data. Abaqus/Explicit and Abaqus/Implicit is used for the modeling and structural simulation of the polymer films. Several statistical data analysis tools are used to extract and compare the structural data. Simulations are performed for most of the physical tests on individual layers. Physical test results will be compared to the virtual results to validate the test method and results.
2. Theoretical Model

2.1 Basics of Fracture Mechanic in polymer films

Fracture mechanics is the field of solid mechanics that deals with the behavior of cracked bodies and subjected to stress and strains. The most successful application of fracture mechanics is to fatigue[6]. Power of fracture mechanics lies in the fact that local crack tip phenomenon can be used to calculate the global parameter values[7].

Fracture mechanics describe the behavior of solid or structures with geometrical discontinuities at the scale of structure. This continuity can in the form of line discontinuity in two dimensional media (plates and shells) or surface discontinuity in three dimensional media.

Different industries use different materials and have different types of fractures depending upon type of loading. Different types of loading occur during package transportation and opening [8]. These loading can be studied using different modes of failures. Different test can be performed on the material in different direction due to its anisotropic behavior to calculate material parameters.

Fracture of engineering materials is often preceded by considerable changes in the microstructure of its material. For highly ductile material fracture process zone is large and crack tip fields are no longer adequately characterized by J-integral only. The micro structural damage model is both material dependent and geometry dependent as compared to conventional model which is only material dependent[9].

In case of highly ductile materials elastic–plastic fracture mechanics (EPFM) which uses the J-integral, CTOD methods and strain energy density techniques are used[10].
2.2 Modes of Failure

Fracture Mechanics involves three ways of applying force to enable a crack to propagate through the material. These forces act in a unique way to create a mode of failure i.e. as shown in Figure 2.1.

Mode I crack – Also known as opening mode, Tensile stresses normal to the plane.

Mode II crack – Also known as sliding or shear mode, Shear stress parallel to the plane of crack and perpendicular to crack front.

Mode III crack – Also known as Tearing or out-of-plane mode, Shear stress parallel to plane of crack and parallel to crack front. Crack moves 90 degree or normal to the plane of applied forces. That’s why it is known as out-of-plane mode.

2.3 Mode III Crack Propagation

Trouser tear test is one of the simplest method to determine the stiffness of a self supporting polymeric film in out of the plane [12]. The tearing behavior of materials is a major component of their mechanical performance. In the research community, large efforts have also been devoted to the understanding of the tearing behavior of materials.[13]
Fracture Energy for a propagation crack is directly proportional to
\[ \int_{0}^{2\pi} x(\theta) |\sin \theta| d\theta \]

And ‘x’ is the distribution function of the molecular orientation measured experimentally. \( \theta \) is the angle between direction of propagation of crack and local molecular orientation in its path. \(|\sin \theta|\) is the resistance by local molecular structure to propagating cracks, which is maximum for perpendicular crack direction and which is minimum for parallel crack direction[12].

2.4 Essential Work of Fracture and Tearing Behaviour

2.4.1 Introduction of Essential Work of Fracture

The essential work of fracture method (EWF) to evaluate the fracture toughness of ductile materials in plane stress with prevalent gross yielding conditions was originally developed by the Cotterell-Mai[14] research group in Sydney University more than ten years ago. Since then, the EWF method has been proven independently by many researchers to be a valid tool for a range of ductile metals, polymers, paper sheets and fibrous composites.

The basic concept of Essential work theory is the separation of total fracture energy of a pre-cracked specimen into geometry dependent (non-essential work) and geometry independent (essential work) components. The essential work of fracture is used to describe the tearing behavior and deformation of thin ductile polymers e.g. LDPE and PP. Several experiments have been performed to get the values of certain inputs like modulus of elasticity, plasticity values and poison ratio, toughness, plastic and elastic stresses and strains. These stresses and extensions are used to calculate the essential work of fracture.

The area closest to the crack initiation and runs along the crack is process zone. The area that surrounds this process zone is the plastic zone as shown
in Figure 2.2. The work done by tearing or crack propagation in process zone is called essential work and the work done in plastic zone is called non-essential work of Fracture. European structural integrity society has recently developed the method and specimen to calculate the EWF. The specimen geometry and different process zones present are shown in fig 2.2 using ESIS protocol.

Essential Work of Fracture Specimen (ESIS Standard)

![Diagram of Essential Work of Fracture Specimen zones for Tensile Test using ESIS protocol](image)

*Figure 2.2 Essential work of Fracture Specimen zones for Tensile Test using ESIS protocol [15].*

2.4.2 Essential Work of Fracture Parameter Calculation

The essential work of fracture is directly related to the energy for creating the surfaces of new cracks in the process zone. The non-essential work of fracture is related to the formation of the plastic zone around the process zone.

Considering the size of the process zone and the volume of the plastic zone. The concept of EWF test was well-described by Cottrell and Reddel [16]. Two types of specimen, i.e., single-edge notched tension (SENT)
specimen and deep double-edge notched tension (DDENT) specimen, are commonly used for EWF tests. Figure 2.3 presents the schematics of the concept of EWF tests for DDENT specimens. The total work of fracture ($W_f$) can be separated into two components, i.e., the essential work of fracture ($W_e$) and the non-essential work of fracture ($W_p$).

$$W_f = W_p + W_e$$

![Diagram showing EWF Parameters calculations](image)

**Figure 2.3 EWF Parameters calculations** [17]

The essential work of fracture (EWF) concept was proposed by Bromberg. Some researchers ([18][19][20]) expanded this concept to various cases. Recently, the European Structural Integrity Society (ESIS) published a test protocol for EWF tests of thin polymeric films to initiate the standardization of EWF tests. Due to a large amount of plastic deformation around the crack tip of polymeric thin films as soon as the tear load is applied, the tear process can be assumed as the propagation of a mode-I crack. Therefore, the fracture toughness of polymeric thin films under tear loads can be estimated by EWF tests. There have been reports on the application of EWF tests for evaluating the fracture toughness of various polymeric thin films but only limited studies are available for the evaluation of the fracture toughness of thin elastomeric materials.
Several experiments have been performed using the ESIS standard geometry for PP and LDPE. The results are shown here in the form of force-displacement curves. EWF can be calculated by taking the integral of these curves for each ligament length. Tests are performed from 4-12mm ligament length as shown in figure 2.4 and Fig 2.6 respectively for PP and for LDPE

![Diagram of Essential Work of Fracture PP DENT](image)

**Figure 2.4 Load vs. Displacement values for EWF of PP at Different Ligament Lengths (4mm-12mm).**

Essential work of fracture for PP and for LDPE has been calculated from the experimental tests. These tests are performed to get the understanding about the fracture toughness of the material. The essential work of fracture for PP is shown in Figure 2.4, and for LDPE is shown in Figure 2. The essential work of fracture is used to determine the crack initiation stress and displacement,

- Force-displacement graphs are obtained from experimental tests at different ligament lengths starting from 4mm-12mm lengths.
- The materials have shown a constant increasing behavior in linear
- PP shown a brittle fracture while LDPE shown a very ductile fracture. Blunting phenomenon is also seen for both materials.
- Crack propagation or fracture growth rate is slightly faster for PP than for LDPE.
- LDPE being very ductile requires small force to start and propagate a crack than PP which is very stiffer.

![Diagram of elastic energy release after fracture test](image)

**Figure 2.5** Effect of elastic energy release after fracture test a) initial stage b) crack propagation c) end of fracture d) elastic recovery [15].
It is quite evident from the experimental tests that there is a large amount of yielding for ductile materials like LDPE before fracture as shown in Figure 2.6.

A linear relationship is seen between force and displacement.

The fracture or crack propagates after the complete yielding. Yielding is predominant for the ductile material and only blunting is visible for low extensible materials like

The crack starts to propagate until the ligament length gets fractured and an elastic recovery is seen on the separated edges of ligament as described in Figure 2.5.

### 2.5 Stress concentration

Stress concentration (different shape crack base on this) shown in Figure 2.7.
The degree of the stress concentration have a relationship with how sharp the crack will be, the sharper the crack the higher degree of the stress concentration will be schematic of stress concentration is shown in Figure 2.7. Different crack shapes have different fracture properties and fracture criteria. This will make the real fracture strength have a very large different with the actual fracture strength. The geometry of an elliptical crack is shown in Figure 2.8.

$$\left(\sigma_y\right)_{\text{max}} = \sigma \left(1 + 2 \frac{a}{b}\right)$$
So if \( a=b \), it will be circle crack, stress will be:

\[
\sigma_{\text{circle}} = \frac{(\sigma_y)_{\text{max}}}{3}
\]

And if \( 2a=b \), it will be ellipse crack, stress will be:

\[
\sigma_{\text{ellipse}} = \frac{(\sigma_y)_{\text{max}}}{2}
\]

So it will have:

\[
\frac{\sigma_{\text{circle}}}{\sigma_{\text{ellipse}}} = \frac{2}{3} = 0.667
\]

And

\[
F = \frac{\sigma}{A}
\]

If the cross section is same, the relationship for force will be same as the relationship for stress.

In the after work the same is performed by physical test and simulation using Abaqus.
3. Experimental Setup and Testing

3.1 Experimental setup

The experimental focus of this research thesis is on different test cases to extract the data to determine the material properties. The material properties are needed to calibrate the material model in FEM simulations to perform the virtual tests. The experiments are performed on continuum material in principal material directions namely MD, CD and 45 degree to MD direction. A damage criterion is introduced into the numerical material model to predict the opening or crack initiation and crack propagation. Ductile damage or crack is also introduced as different shapes like flat, circular and ellipse for experimental testing. Trouser tear testing is also performed for different material direction.

Experimental material used for testing is biaxial oriented Polypropylene (PP) and low density polyethylene (LDPE). PP material is provided by Tetra Pak Packages AB at Lund and LDPE is provided by BTH material Lab at Karlskrona. PP has a material thickness of 18 µm and LDPE has a thickness of 27µm. Continuum material tests are performed for PP and LDPE. Different crack shapes tests are performed for PP. Trouser tear tests are performed for both PP and LDPE.

![Polypropylene (PP)](image)

*Figure 3.1 Polypropylene (PP)*

Test cases include single layer tensile tests for continuum material PP and LDPE and trouser test for single layer PP and LDPE. Different crack shape or damage tensile tests are done for PP only. The complete summary of the
experimental tests is as shown in figure 3.1. These experiments are performed in Tetra Pak packages Lab at Lund and BTH material research lab at Karlskrona.

**Test cases (Experimental and Numerical)**

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<th>Numerical Test</th>
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<td>CD/MD(PP)</td>
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<tr>
<td><img src="image2.png" alt="Image" /></td>
<td>CD(PP)</td>
<td>CD(PP)</td>
</tr>
<tr>
<td><img src="image3.png" alt="Image" /></td>
<td>CD/MD/45°(PP&amp;LDPE)</td>
<td>CD/MD(PP)</td>
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*Table 3.1a) Experimental and Numerical Test Cases performed*

### 3.2 Experimental material, directions and size

PP material is used for the tests. When polypropylene is stretched and extruded at the same time in Machine direction and cross direction, a new material is formed. This material has been used here to perform the all the tests and to extract material properties. The material is supplied by package and packaging material manufacturing company Tetra Pak Packaging Solutions AB. PP is assumed as anisotropic material.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness</th>
<th>Type</th>
<th>Provider</th>
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</thead>
<tbody>
<tr>
<td>PP</td>
<td>18µm</td>
<td>Single layer</td>
<td>Tetra Pak</td>
</tr>
<tr>
<td>LDPE</td>
<td>27µm</td>
<td>Single layer</td>
<td>BTH</td>
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</table>

*Table 3.1b) Experimental Materials*
For tearing test, it is required to find the property of the material and also its behaviour, due to which all the three directions (MD, CD and 45° direction) are needed to be studied. However, the simulation is performed for only MD and CD direction.

Specimen size and geometry for continuum material test is depicted in figure 3.3. Five samples are tested in each material direction to get the repeatability. Material properties are extracted from continuum material tensile testing. Different crack shapes i.e. flat, circular, elliptical are also tested with same specimen geometry in cross direction (CD).
Different crack shapes are tested using same specimen geometry as continuum and all cracks have 10mm centre crack. Experimental testing and numerical simulation are performed for cross direction specimen only. Continuum material tensile test for PP & LDPE are also shown in figure 3.1 and figure 3.3a.

**Figure 3.2 PP 10 mm Flat, Circular & Elliptical Crack**

**Figure 3.3a) Continuum material Tensile test for LDPE (20*25)**

### 3.3 Tensile Experimental Testing and Results

Tension test use the MTS machine at the laboratory, Blekinge Institute of Technology (BTH). MTS machine has two grippers to clamp the specimen, the lower one is stationary and the upper one moves up by set a
displacement on the cross head. Test use 2.5KN load cell, the specimen placed between the gripper. Then the upper grippers will move up until the specimen breaks. The speed is set as 7mm/min. Computer connected with the machine will record the displacement and load automatically.

![Image](image-url)

**Figure 3.3b) MTS Q100 Test Facility at BTH Lab, Karlskrona, Sweden.**

### 3.4 10 mm flat central crack test result

Five specimens are tested to get the repeatability and to see if the method and equipment used is appropriate for testing. Very fine and repeatable results are obtained in each material direction. The one graph for cross direction is shown in figure 3.4. Repeatable test results are shown in Appendix B. The polymer material usually shows anisotropic material behaviour, so these polymers are tested in different directions to measure the forces in all these directions. Experiments are performed in MD, CD and 45 degree to MD for PP.
From the figure it is observed that the material fracture between 2.2-2.6mm and a mean value of the result is used here to present. The convergence method is also followed in simulations of this test to get a mean value. All principle material directions shown a good repeatability and anisotropic material behaviour is observed.

### 3.5 Different Crack shape tests and Results

#### 3.5.1 Specimens prepared by laser cut for circular and elliptical hole

This test is a very interesting test, but one big problem for this test is on how to prepare the specimen, it is easy to find a punch to make a circle hole, but it’s difficult to find a tool to make elliptical hole.

Tetra Pak consists of a machine which uses laser as its means to cut geometries. But when doing this, tends to change the properties of the material at the boundaries due to the heating effect.
Figure 3.5 PP Circular & Elliptical Crack, Laser Cut at Tetra Pak

Figure 3.5 shows a dark zone around the hole which is due to heat effects because of laser. An extra thin layer is formed on edges due to heat by laser cutting which change the material damage properties to a certain extent.

The aim of the test is to find the material properties of the specimen. However if the laser cutting tends to change these properties, then laser cutting is not a good idea.

In the Tetra Pak lab a circular punch is available. Thus it is possible to obtain a circular crack by mechanical means. Then a comparison with the result by laser cut and punch cut can be made.

The way to do the test is the same as for the tensile test, after obtaining the results, comparison is made.

Figure 3.6 PP Circular Crack Physical Test (Mechanical cut & Laser cut)
Figure 3.6 shows the a circular hole obtained by heat or laser cut will greatly change the property of the polymer, so the test cannot continue with this way, for it will get a trick result. This means laser cut is not a good way to cut plastic, in the future when someone want do this kind of test should avoid to use this way to cut your material.

3.5.2 Specimen prepared by Mechanical cut at Tetra Pak AB and at Water Jet AB

For circle shape crack, mechanical punch is used, as it has been mentioned before, it is easy to cut it with a punch. In-case of an elliptical hole, several ways have been tried, and finally a good way was found. Mechanical Punchers are provided by Tetra Pak Packaging & filling Machine Prototype department as shown in figure 3.7.

![Image of Mechanical Punchers provided by Tetra Pak.](image)

*Figure 3.7 Mechanical Punchers provided by Tetra Pak.*

Two dies were made with the help of water-jet cutting in the company Water Jet, Ronneby. The die is as figure 3.8 shows:
To prepare the test specimen, we need: PP, the cutting Die, scalp and tape. The tape is first put on the material on the place where the hole is to be made. Then die is then placed properly at the centre of the specimen and cut using the scalp on the side not containing the tape.

3.6 Experimental Test Results for different Crack Shapes:

The graph curve is exactly the same as for the circular curve except that the breaking point extends further as shown in Figure 3.9:

![Graph showing comparison between Circular Crack and Elliptical Crack](image)

*Figure 3.9 Comparison of Circular Crack Vs Elliptical Crack, Physical test (more physical test result can be found in Appendix)*
Based on the theory, the relationship between the force should be 0.667 i.e. force for circular crack should me 0.667 times that of the elliptical crack. In the test performed it is arrived at $155.6/244 = 0.638$. The physical result has a good match with the theory.

### 3.7 Conclusion of tensile test

After the entire tensile test, a Figure 3.10 combined with PP no notch result, 10mm central crack result, circular crack result and elliptical crack result as shown in figure 3.11.

![PP Tensile Test](image)

*Figure 3.10 Combine tensile tests with no notch, 10mm crack, circle and ellipse*

From this figure 3.10, it can be found that the entire tensile test PP with different crack goes the same trend as PP no notch, the difference is they break at different point of the no notch result. This means when we do the simulation for PP tensile test, the same material property can be used for the entire tensile test. Only fracture or damage criteria are changing but all the curves are coming on the same line as continuum material.
3.8 Tearing Test Method and Experimental Test Results

3.8.1 ASTM 1938-08 Tearing Test Standard Method

A common technique to measure the critical fracture energy during fracture of rubber-like materials is the trouser tear test. This method got its name because a rectangular sheet cut along its axis to form a trouser-shaped specimen as shown in figure 3.11. The legs of the trouser specimen are pulled in opposite direction for a certain extension to create the tearing action. The tear crack always moves at 90 degree out of plane from the applied force direction. The significance of this method is that critical energy release and crack propagation rate is independent of the specimen geometry and crack length.

This test method covers the determination of the force necessary to propagate a tear in plastic films (less than 0.25mm thickness) and thin sheeting materials (less than 1mm thickness) [7]. This test method employs a constant rate of separation of grips holding the test specimen. Specimen extension is measured by grip separation. This Test method for tear resistance propagation is similar to ISO 6383-1 for tear resistance Trouser Test method.

Trouser Tear Test Specimen Geometry is shown in Figure 3.11

![Figure 3.11 Schematic of Trouser Tear Test Specimen geometry](image)

a) Trouser Tear sample  b) Trouser Tear specimen geometry
In Trouser tear test method, force necessary to propagate a tear across a film or a sheeting specimen is measured using a constant rate-of-grip separation machine (Instron 5655 in this case) and it is calculated from load displacement or load time chart.

The significance of this method is evident from the fact that the test method is of value in rating the tear propagation resistance of various plastic films and thin sheeting materials of comparable thickness. For highly extensible films or sheeting the deformation energy of specimen legs is significantly higher than tearing energy [23]. Tearing for highly extensible films (i.e. LDPE) and low extensible films (i.e. PP) can be distinguished from the load time or load displacement graphs. Very fine, repeatable and reproducible force vs. displacement results is obtained using the similar specimen geometry for extensible and non extensible films and sheeting.

3.8.2 Specimen Cutting

![Figure 3.12 Trouser Tear Test Samples Preparation PP](image)

*Figure 3.12 Trouser Tear Test Samples Preparation PP*
A steel ruler and a sharp medical knife or scalpel is used to cut the sharp edge specimens of same geometry as can be seen in Figure 3.12. A 25mm pre crack is produced in each specimen before mounting the specimen in grippers.

Care needed for specimen cutting and mounting on grippers

- The gripper size is 25mm so a 40mm extra leg is made for each specimen as shown in above specimen geometry for each material direction.
- PP is very sensitive so a little slack of 2 mm is given so no crack initiation happens.
- Extreme care is needed while mounting the specimen in grippers so that crack edge remains sharp and no crack initiation happens before the test start.
- For accurate repeatable results sharp blades should be used.

Test equipment includes an Instron 5565. This Instron 5565 is used to perform the standard trouser tear tests at Tetra Pak research facility. A load cell of 100N is used due to small tear propagation force for the specified material. Instron uses Bluehill 2 software to calculate the load, time and extension values. The lower gripper is fixed while the upper gripper moves at a constant rate of 7mm/min in this test case as shown in the Figure 3.13.

![Instron 5565 Setup](image)

*Figure 3.13 MTS Instron Facility, Tetra Pak Lund, Sweden.*
Figure 3.15 shows the experimental results for the trouser tear test for MD, CD and 45 degree to MD. It is observed that the maximum force is in 45 degree direction and the minimum force is in the cross direction. While for machine direction force is more close to the force in 45 degree direction.

![Figure 3.14 Fractured Samples in MD, 45 and CD direction](image)

There is a rapidly increasing higher peak force in all these tests which is corresponding to the initial gradually increasing damage zone ahead of the propagating crack[19]. The tear curve level off at a constant load once the crack has initiated for the low extensible films like PP. This constant load shows that the damage zone reached a constant width on each specimen leg. The tearing fracture of PP film material in principle material directions MD, CD and 45 degree to MD is also shown in a video for better understanding and making the realistic simulations. Link for video is provided in appendix of report.

### 3.8.3 Tearing result

#### 3.8.3.1 Result of PP in material direction CD, MD and 45 degree

The crack follows a straight path for CD direction leaving a constant width of damage or plastic zone on each of the specimen leg. For MD the crack
goes a little towards left but leaving a constant damage zone on each of specimen leg as shown in figure 3.14. In 45 degree to machine direction that crack followed a specific angular direction towards left or right depending where it can find low resistance, but again leaving a constant width of very small damage zone on both specimen legs.

Some tests are performed on these PP and LDPE trouser tear samples to know its behaviour for sharp knife cut and for self driven cut as shown in Appendix B. Sharp knife cut means that PP trouser tear specimen is prepared with sharp knife and a trouser test is performed to get its force-displacement graphs, the same specimen is stopped after 20mm extension, re-gripped and started again and it gives a low or small value than previous one which is almost as low as half of original value.

![PP Tearing Test (Physical)](image)

*Figure 3.15 Trouser tear test result for 45, MD and CD direction.*

While for LDPE which is highly extensible it gives opposite behaviour i.e. after every extension it gives higher value of force–displacement as shown in Appendix B. Same test is performed for Aluminium laminate and it showed same increasing behaviour as LDPE. Graphs for aluminium tensile test and tearing Aluminium laminate are not included here.
3.8.3.2 Result of LDPE in material directions MD and CD

The tearing in ductile or soft films creates a large and visible plastic zone. The above image of the torn film shows a continuous yielded zone on either side of the fracture. The film LDPE used for tearing tests here has a thickness of 27µm. The film is torn in two directions namely, MD (machine direction) and CD (cross direction) to see anisotropic or isotropic behaviour of the film. After testing the LDPE in these directions, the film showed higher stiffness in CD than MD.

![Graph showing force vs. extension](image)

Figure 3.16 Tearing of Ductile material i.e. LDPE under zonoscope showing different zones

The Figure 3.16 explains the MD and CD curves for the LDPE. From the graphs and also from the photos it is quite evident that LDPE has a higher plastic or damaged zone and also the forces are higher in the CD material direction. Here are some important prerequisites for soft or ductile films like LDPE are:

- Tearing of thin ductile polymer film LDPE is a mix mode failure i.e. tearing and deformation are the predominant phenomenon. So it is a mixture of Mode I (deformation) and Mode III (tearing).
• Due to large deformation in the each leg during trouser tear test, extension in the film is much higher than the original length of specimen leg.
• Crack propagates after the material has been fully yielded.
• The whole yielding and tearing process is shown in a video format for better understanding of ductile tearing. Links to video are provided in the appendix.

3.8.3.3 Trouser Tear Relax or Loading unloading Test for PP
Trouser Tear Relax test is performed on specimen to calculate the tearing work done and tearing energy required to tear off the specimen as shown in figure 3.18.

![Figure 3.17 Tearing Loading and unloading Test for three material directions of PP](image)

Forces applied to trouser tear test is plotted against the extension of test specimen for three different anisotropic material directions, namely, machine direction (MD), cross direction (CD) and 45 degree to machine direction. Figure 3.17 explains the tearing behavior in a simple and comprehensive way. Arrow 1, showing how much force is needed to start a tear crack, arrow 2 indicates the constant force F needed to propagate a crack, and arrow 3 indicates the final retraction of the specimen as forces is removed from the test specimen. The non linear parts of the curve at arrow
1 and arrow 3 in the Figure 3. indicate the stored energy in the legs of the specimen.

Small fluctuations in the tear crack propagation behavior are not due to noise but they are due to stick-slip behavior observed in thin polymer films fracture. Maximum fluctuation represents the crack growth and minimum represents the crack arrest[22].

- The interval of these fluctuations is related to the morphology of the material such as distribution of crystalline and amorphous phases which is more structurally described in microscopic part of this report.
- The irregular deformation ahead of crack tip is also described by SEM photographic results as shown in Appendix B.
- The higher peak forces for CD and a little peak for MD is also explained by SEM results in appendix B.

### 3.9 Tearing Energy and Work Done Calculation

The critical fracture energy from a tear test also known as tearing energy is the energy spent per unit thickness per unit crack length. The tearing energy includes the surface energy, energy dissipated in plastic flow and energy dissipated in viscoelastic process [24]. Trouser tear test has an advantage, the tearing energy only depends on the crack length and deformation in the vicinity of crack tip, hence energy is independent of shape and the way forces are applied.

Work done during Trouser Test is given by[25],

\[ \Delta W = 2F \Delta c \]  

(1)

\( F \) is the tearing force and \( \Delta c \) is the tear distance [26].

The tearing energy or the critical fracture energy is given as,

\[ T_c = \frac{\Delta W}{B \Delta c} \]  

(2)

B is the thickness of specimen. Combining above two equations:
From the above equation it is quite evident and clear that tearing energy is independent of initial geometry and crack length and only depending on thickness.

\[ T_c = \frac{2F}{B} \]  \hspace{1cm} (3)

Using the equation 1 and 3, tearing work done and the critical tearing energy of the tested materials i.e. PP and LDPE is calculated. The extracted data from these experiments is quite useful for calculation of different material parameter as shown in table 2 Results of Tearing Test material properties. The experimental environmental conditions are also explained in material properties Table. The table explains the whole summary for trouser tear test and tensile testing.

### Table 3.2 Tensile and Tearing Test Result Summary

Using the equation 1 and 3, tearing work done and the critical tearing energy of the tested materials i.e. PP and LDPE is calculated. The extracted data from these experiments is quite useful for calculation of different material parameter as shown in table 2 Results of Tearing Test material properties. The experimental environmental conditions are also explained in material properties Table. The table explains the whole summary for trouser tear test and tensile testing.

<table>
<thead>
<tr>
<th>Polymer Material</th>
<th>Film Thickness (µm)</th>
<th>Tearing Force [mN]</th>
<th>Critical Tearing Energy [N/m]</th>
<th>Tearing Work (N.mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP</td>
<td>18</td>
<td>MD 54</td>
<td>6051±50</td>
<td>5.45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CD 24</td>
<td>2677±50</td>
<td>2.43</td>
</tr>
<tr>
<td></td>
<td></td>
<td>45 68</td>
<td>7556±50</td>
<td>6.81</td>
</tr>
<tr>
<td>LDPE</td>
<td>27</td>
<td>MD 750</td>
<td>555561±50</td>
<td>90.21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CD 3000</td>
<td>222.222.2±50</td>
<td>360.12</td>
</tr>
</tbody>
</table>

### Table 3.3 Results for Tearing Test material Properties

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Material Direction</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength(N)</td>
<td>MD</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>CD</td>
<td>73</td>
</tr>
<tr>
<td>Tensile Elongation(mm)</td>
<td>MD</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>CD</td>
<td>30</td>
</tr>
<tr>
<td>Tearing Strength(mN)</td>
<td>MD</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td>CD</td>
<td>24</td>
</tr>
<tr>
<td>Tearing Elongation(mm)</td>
<td>MD</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>CD</td>
<td>50</td>
</tr>
<tr>
<td>Modulus of Elasticity (%)</td>
<td>MD</td>
<td>2174</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>3721</td>
</tr>
<tr>
<td></td>
<td>CD</td>
<td>4741</td>
</tr>
<tr>
<td>Poison Ratio</td>
<td>MD</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>CD</td>
<td>0.3</td>
</tr>
<tr>
<td>Conditioning( °C)</td>
<td>MD</td>
<td>23±1 °C</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CD</td>
<td></td>
</tr>
</tbody>
</table>
4. Numerical Analysis and Simulations Using Abaqus:

4.1 Introduction

Numerical modelling and analysis is used in order to achieve a more in-depth understanding of the physical tests through their replication in virtual environments.

Finite Element Analysis Software Abaqus 6.12 is used to perform numerical modelling and analysis. Tensile and tearing crack propagation simulations are performed to validate the nice experimental results. For this purpose tensile samples with different crack shapes are modelled and analyzed to get converging results. Results are calibrated to get quite matching results with experimental values. Tearing model is also simulated and calibrated.
Abaqus is basically modelling and FE-Analysis software used extensively in the analysis regime today. It has four modules depending on the application it is intended for as follows. The simulation is done in Explicit due to the need for using shell elements for reducing computational time. Also in Explicit, the time increment is dependent on the smallest element size, due to which it isn’t possible to carry the simulation in natural time scale and needs to be accelerated to a great extent.

4.2 Calibration of Material Properties

4.2.1 Young’s Modulus (E)

It is measure of Elasticity of a material. In general it is defined as the ratio of Stress and Strain. It is the slope of a Stress-Strain plot in the elastic region.

$$E = \frac{\text{Stress}}{\text{Strain}} = \frac{\sigma}{\varepsilon}$$
4.2.2 Plasticity (Ductile Materials)

We should use the True Stress and True Strain Values rather than the Engineering (Nominal) Stress and Engineering (Nominal) Strain Values to account for the change in cross-section in each time interval during the testing.

Engineering Stress:

\[ \sigma_{\text{engineering}} = \frac{\text{Change in Length}}{\text{Original Length}} = \frac{\Delta L}{L} \]

Engineering Strain:

\[ \varepsilon_{\text{engineering}} = \frac{\text{Force}}{\text{Cross-sectional Area}} = \frac{F}{A} \]

True Stress:

\[ \sigma_{\text{true}} = \sigma_{\text{engineering}}(1 + \varepsilon_{\text{engineering}}) \]

True Strain:
\[ \varepsilon_{\text{true}} = \ln(1 + \varepsilon_{\text{engineering}}) \]

However for the tearing simulation, we were unable to accurately determine the plasticity values according to the formulae’s above due to lack of time and resources. For this thesis we have physically manipulated the plasticity values in order to fit the physical test curve.

### 4.3 Mesh density of PP Tensile Test Simulation Research

Abaqus is software based on FEM method, and FEM method is highly meshing dependent. The more element number used the more will be the accuracy of the simulation result. But there will certainly come a point beyond which even if we increase the number of elements, the result will be nearly the same. This is called as convergence. So after that specific number, increasing the elements will not result in any significant changes and will only lead to more test run times. This efficient mesh element size was arrived at by running the simulation for different sizes of the elements till they converged.

Figure 4.3 shows the simulation model, and the zoomed one shows the meshing density increased parts. The element numbers were increased from 6 per 2.5mm to 25 elements per 2.5mm, i.e. decreasing the element size from 0.417mm to 0.1mm.
After these series simulation we can get the result as following:

From the results it is seen, when it comes to 16 elements on 2.5mm, which is 0.015625mm per element, the result starts converging. Thus it was finally
concluded that this is the ideal mesh element size for carrying out the simulation tests result.

After modifying the input properties the simulation result were obtained. Comparing with the physical result and simulation result it is seen that they match perfectly fine. The input material properties of 5 mm tips crack for PP are as follows,

Figure 4.5 PP Tensile test, Numerical Vs Physical test.
4.4 PP CD direction different shape crack simulation

4.4.1 Assumptions in Modelling

1) Poisons ratio = 0.3
2) Material is isotropic & linear elastic
3) Material is homogenous.

4.4.2 Modelling steps

Steps involved in modelling are as follows:

Part:

3D, Deformable, Shell, Planar structure is used to construct the base specimen. Consider the model is symmetry with the right and left part, so half of the real specimen is used in the modelling. The part model for circle crack and ellipse crack is as the follows
**Figure 4.7 Numerical Model**

Property:

For the tensile material parameters, see Appendix B.

**BC:**

Here initially constrain all the degrees of freedom for displacement and rotation except for displacement along the Y-axis.

Then a displacement of 15mm is given on the top left point for circle crack simulation, and 35mm on the top left point for ellipse crack simulation, both of the displacement should set with the amplitudes set in the last step.

**Figure 4.8 Boundary Conditions Imposed**

Mesh:
In mesh part, media axis method is used to mesh for different crack, with this the elements can be made more structure around the crack. The advancing Front Method which was previously used does not give a proper distribution of elements. The difference between two is as follows

Figure 4.9 Numerical Model, Element Type Alignment

Job:

After selecting all the material properties and the boundary conditions, a job is created and submitted for the analysis.
4.4.3 Simulation Result

After the job is submitted and completed successfully, results are available to see. Stress concentrations, crack propagation and forces and displacement analysis are done in this part.

![Numerical model Crack Progression, Circular Crack](image)

*Figure 4.10 Numerical model Crack Progression, Circular Crack*

The force and displacement values obtained from the Numerical simulation and plotted in a Force Vs Extension graph along with the Physical test result.

![Numerical Result Vs Physical Result](image)

*Figure 4.11 Circular Crack Comparisons of Physical Vs Numerical*
The Physical and Numerical result’s show a good fitting Similarly to the circular crack simulation, the result for the elliptical crack is obtained.

![Figure 4.12 Numerical model Crack Progression, Elliptical Crack](image)

![Figure 4.13 Elliptical Crack Comparisons of Physical Vs Numerical](image)
Even in this case, both the plots are quite identical.

### 4.4.4 Conclusion of different shape of crack

In the physical test result of different shapes of cracks, ratio between the maximum force between circle crack and ellipse is 0.638. In Figure 4.14, physical result and numerical result are plotted together for circular crack and elliptical crack. From the figure it can be clearly seen that the ratio of numerical result for different crack shapes is $\frac{161.2}{260.832}=0.6145$. The theoretical relation is 0.667.

From this we can conclude that there is fairly decent match between the physical test result, the numerical test result and the theoretical value.

![Figure 4.14 Circular & Elliptical Crack Comparisons, Physical Vs Numerical](image-url)

<table>
<thead>
<tr>
<th></th>
<th>Physical Test</th>
<th>Numerical Test</th>
<th>Theoretical</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F(\text{Circular})/F(\text{Ellipse})$</td>
<td>0.638</td>
<td>0.6145</td>
<td>0.667</td>
</tr>
</tbody>
</table>

*Figure 4.14 Circular & Elliptical Crack Comparisons, Physical Vs Numerical*
Here comes to the conclusion:

1. It is quite evident from figure 4.14 that the three results are in a very close match and it also shows that that the physical test methods and FEM numerical modelling strategy is absolutely correct.
2. The numerical model parameters are extracted from experimental tests and give so similar results.
3. The specimen cutting techniques for all these shapes (flat, circular, and ellipse) are also proved appropriate.
4. Regarding numerical part, the meshing method, material model are also kept similar with changing only in the fracture strain values which is always different for different shape of crack.

4.5 Tearing Tear Test simulations of PP in CD and MD direction

4.5.1 Assumptions in Modelling

Same as different crack shape tensile modelling, the tearing simulation work also have the following assumptions:

1) Poisons ratio = 0.3
2) Material is isotropic & linear elastic
3) Material is homogenous.

4.5.2 Modelling steps:

Steps involved in Tear test modelling are as follows,

Part:

Modelling work use 3D, Deformable, Shell, Planar structure to construct the base specimen. This modelling work for tearing have a very large different from the tearing simulation work have been done before. A flat shelled modal is used at the beginning instead of a two legged modal, since when using a two leg modal there arises a need to specify a fillet radius. The two models are as follows
Property:
For the material parameter values, see Appendix B.

BC:
Here initially constrain all the degrees of freedom for displacement and rotation except for displacement along the Z-axis. Then a displacement of about 26mm is given to both the legs in opposite directions. Although this is against only move with the upper edge in the real physical test, but this way have an obvious advantage that will be less warping for the specimen.
Mesh:
Tearing simulation used this way is highly based on the meshing density, the smaller element size we set the better result we will get, because of the limit of our computer ability, and we set 0.01mm for the element beside axial wire.

![Meshing in Elliptical Model](image)

*Figure 4.17 Meshing in Elliptical Model*

Job:
After selecting all the material properties and the boundary conditions, the job is created for submitting for the analysis.

4.5.3 Simulation result
Here it mainly focuses on the force since it being the basic variable element. “Force Vs Displacement” is made for the purpose of observing the behavior of the specimen. At the same time the stress distribution views are also.

<table>
<thead>
<tr>
<th>Position</th>
<th>Von Mises (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crack Initiation</td>
<td>97.3</td>
</tr>
<tr>
<td>Crack Propagation</td>
<td>90-97</td>
</tr>
</tbody>
</table>

*Table 4.1 PP tearing stress*
Figure 4.18 Stress Distributions for Tearing Model

The specimen performance in Abaqus as figure 4.19 shows, and the performances are same between MD and CD direction.

Figure 4.19 Tearing Numerical Model

Then we plot the numerical data together with the physical data we get before:
Figure 4.20 Physical Tearing Test Cross-Direction, Physical Vs Numerical

Figure 4.21 Physical Tearing Test Machine-Direction, Physical Vs Numerical
From figure 4.20 and 4.21, it is seen that the numerical result and the physical result have a good match except the numerical result have larger amplitude than the physical result.

### 4.5.4 Tearing simulation conclusion

From the above plots it is seen that there is a significant difference between the Numerical tests and the Physical tests. This is due to the reason of Element Size. In the physical material specimen the tearing takes places right at the inter-molecular level. Where as in the numerical model the tearing takes place due to the deletion of elements and is thus dependent on the size of the elements. Thus smaller the element size smaller will be the distance between the peaks and valleys in the tearing plot. Below is a plot for element size of 0.1 and 0.2 mm. It is observed that gradually reducing the element size leads to a reduction in distance between the peak and valleys, which eventually will lead to a perfectly identical match between the numerical with the physical.

![Numerical Result (Different Element Size)](image)

*Figure 4.23 Result comparisons for PP tearing with different meshing element size*
However considering the total length of the specimen it is not possible to reduce to element to a very low size due to computational time and efficiency. There should be a proper trade-off between the element size and run time.

### 4.6 Discussion of material property set in the simulation

The plasticity values are initially obtained from the No-Crack specimen. And the same is used for all the test specimens of PP of different cracks with same dimensions. Due to this the results obtained with the Physicals tests and the Numerical tests are not accurately overlapping. The break point from the Numerical test varies from the Physical test.

![Different shape of crack result comparison](image)

**Figure 4.24 Different shape of crack result comparison**

This is due to the reason that due to the No-Crack plasticity values the Numerical results tends to break at the No-Crack path, but only prior since the break point is guided by the crack shape and also the Fracture strain value given. So for sure the plasticity values for each specimen will be different. However the difference being not so significant and also the layout of the plot being the same, it is neglected.

Now the case for the Tearing plot is totally different. The Tearing specimens are already cracked due to the Two-Leg Modal. Further the cracking takes place for a specified length of specimen, which is not the case in the tensile test. Thus the diagonal climbing part in tensile test can be
related to the vertical climbing part in the numerical test and the vertical drop part in the tensile test can be related to the horizontal crack propagation part in the tearing test.

![Graph showing tensile and tearing test results]

**Figure 4.25 Tensile test result comparison with tearing test result**

Calculation of plasticity values is quite tricky for tearing test. In the tensile test there is a specific cross-section whose area can calculated to obtain the stress and strain values. But in the tearing specimen case, there is no cross-sectional area. The force applied acts on the thickness of the specimen only. Thus as such there is no area and thus it is not possible to find the stress and strain values using the normal criteria used in case of tensile test.
5. Microscopic Crack Analysis

5.1 Introduction

Scanning electron microscope is one of the most versatile equipment for the material characteristics and failure analysis of solids and polymers. SEM is a scientific instrument that uses a beam of highly energetic electrons to examine the surfaces and phases distribution of the specimen on a micro scale through the live imaging of the secondary electrons (SE) and back-scattered electrons (BSE). Scanning electron microscope is an important tool for the material and failure analysis. SEM is an excellent and perfect tool to determine the root cause of fracture failure i.e. fatigue, brittleness, ductility, corrosion, adhesion. Magnification in a SEM can be controlled over a range of up to 6 orders of magnitude from about 10 to 500,000 times [28].

Material failure analysis by SEM has importance in Packaging industry for the determination of the crack initiation and evolution values and these values will finally determine the stiffness and strength of the material. SEM analysis describes the crack propagation paths which is important for the opening-cutting solutions of the package. This analysis describes the behavior of the material in different directions to find the best feasible crack propagation path. SEM failure analysis is very important because it provides three dimensional images of the crack specimen for the fractographical study.

The main objective is to get perfect crack behavior that describes material properties on a microscopic level to assist in design problems. Elasticity and brittleness of the materials can be viewed simply using SEM analysis. This microscopic study also revealed the effect of morphology characteristic and crystalline structure on the exact nature of crack propagation in thin ductile and brittle polymer films. Microscopic analysis also provided help in the material model for the virtual tests in the form of material properties.
5.2 SEM Specimen Preparations

Two different kinds of specimen were used

1) Microtome cut Specimen (Cut by a microtome cutter to see inside the edge)
   A microtome is a tool used to cut extremely thin slices of the material known as sections [29]. Microtome cut specimen are useful to compare and differentiate the material structures using the Scanning electron microscope. Material sections can be cut up to 50nm thicknesses. For PP, Aluminium and LDPE a 50µm cut is used to cut through the width. Microtome cut is really useful for deep material analysis. The microtome cut specimen is viewed in polarized light microscope to view the thread like specimen.

2) Simple Specimen (Cut by knife to see the whole crack tip

![Microtome Cutting machine with different cutting thickness 50nm-100µm at Tetra Pak, b) Microtome specimen Cutter](image)

*Figure 5.1 a) Microtome Cutting machine with different cutting thickness 50nm-100µm at Tetra Pak, b) Microtome specimen Cutter*

SEM Operation and Setup:

The scanning electron microscope TM-1000 as shown in figure 5.1 has been utilized at Tetra Pak to take the micrographs of the polymer samples. The microscope uses a software programme named TM-1000. Parts of SEM include specimen stage, vacuum chamber, buttons for on off and a button for specimen exchange. There is also a specimen holder which is
used to adjust the height of specimen before putting it into the specimen stage. The specimen after putting it into sputter coater for argon gas coating is put into vacuum chamber. The specimen holder is put into the specimen stage and adjusted according to arrows. Close the specimen stage and press ‘Exchange’ button and hold a hand on stage for a while until it get ready. Click on TM-1000 software icon to start taking the micrograph.

**Figure 5.2 Operation of Electron Microscope TM-1000 at Tetra Pak**

### 5.3 Results and Discussions

PP is absolutely brittle in all directions. PP and LDPE are stiffer in cross direction (CD) of material than in material direction (MD). PP is stiffer in MD than in CD for tearing and it is due to its brittle material properties. Perfect Sharp edges are hard to cut for tearing specimens as seen in the figures above. There is always a region ahead of crack tip called the process zone it always found and it helps to develop the crack. Long curves found in the cross direction are due to the sharp and stiffer material presence at the crack tip which becomes smooth and sharp as the crack start propagating. Different crack propagation directions are also viewed in the
SEM edge analysis, where MD, CD are always flat and 45 degree direction is more sharp and bent at that direction as shown in SEM results. This crack edge analysis clearly describes the crack propagation directions and material flow directions during crack propagations.

![SEM Figures](image)

**Figure 5.3 PP and LDPE Behavior on SEM Microscope after tearing**

The crack edge cutting describes the crack propagation path. SEM figures has shown it quite well that in tearing of a pre cut specimen the crack follow the low resistance molecular orientation path for the crack propagation. The physical test photos and the SEM crack edge photos showing the similar crack edge path the tearing force will follow to propagate it.

- It is also very important in package opening solutions to determine the crack propagation path to comprehend and control the crack path.
- The force is absolutely small and main driver of the crack propagation is LDPE which has a little higher tear force.
- Ductile failure (LDPE) leaves a rough surface while a smooth surface is observed for brittle failure (PP) as depicted in figure 5.3.
The figure 5.4 showing the fracture process or crack generation and propagation process during a tensile test for continuum materials. During the tensile extension of ductile materials like LDPE, necking and void formation is a common phenomenon.

**Fracture Process**

Voids are formed after complete yielding and these voids coalescence to make a crack. These voids make the crack to propagate in a certain direction and when crack get propagated the material separation occurs. Voids are usually created in the lowest material resistance point and it helps for the crack to propagate in that directions.

- For the ductile materials i.e. LDPE, extensive plastic deformation or necking takes place before fracture.
- For ductile failure as shown in figure 5.4 materials gets separated instead of cracking which happens for brittle like material as seen in PP.
- Propagation is quite slow for ductile materials and a large amount of energy absorption before failure while very fast crack propagation for brittle failure.
The stretching of the LDPE film requires a constant increasing force without any rupture or damage. For PP damage or crack moves at a constant force and no increase in force which is showing the brittle like characteristics of PP as seen in Figure 5.5

Figure 5.6 LDPE Edge Stretching after Trouser Tear Test seen on SEM
Figure 5.6 showing the edges of a stretched LDPE film

![Figure 5.6 showing the edges of a stretched LDPE film](image)

**Figure 5.7 Microstructure of PP 45, MD and CD using Polarized Light**

The general picture involves four main stages: first, the stretching and slippage of longitudinal elements closest to the tip of the crack; then, the crowding of these longitudinal elements on the edges of a Del zone and the transfer of the load to the transversal particle layers held in tension in the so-formed Del zone; third, the stretching and alignment/jamming of these transverse molecules or particle layers; and finally the rupture of the outer transverse layer. These stages proceed cyclically until the whole sample has failed.

- The rough edges of ductile film i.e. LDPE is showing its large plastic deformation and a large amount of energy absorption before failure.
- The large amount of plastic deformation seen in the stretched ductile film i.e. LDPE is used to dissipate the energy at the crack tip which exists due to stress concentrations.
- This energy can also create small cracks or voids on the deformed edges which can lead to fracture as seen in figure 5.6.
Figure 5.8 Continuum PP edges showing elongation after Tensile test under SEM
6. Concluding Remarks

6.1 Summary

Using the theoretical and experimental Analysis, many repeatable and reproducible graphs and figures are produced. By comparison to the actual physical evidence produced through the experimentation and numerical results achieved through Abaqus, the two were very close to a great extent. Most crack configurations lead to microscopically mixed mode crack growth. Crack is following Mode III for PP, while for LDPE a mix mode is observed. Interestingly, reproducibility and simplicity of test is visible even for less extensible or brittle material PP. The more ductile the material is, the more it will behave in mix mode crack propagation.

Crack growth rate is much faster in Mode I than in mode III and it is very much faster for low extensible materials (PP) than highly extensible materials (LDPE). Crack moves at an infinite fast rate in Mode I and almost under no control. High speed cameras and special software techniques are used to observe the crack propagation in slow motion. For Mode III crack moves at a constant rate of grip separation and crack propagation is under control. From physical results it is quite evident that it is always mix mode crack propagation. From a microscopic point of view, the occurrence of pure mode III crack front segments seems also to be highly improbable. Moreover, pure mode III crack propagation does not appear to have plausible support from a theoretical point of view. A complete Mode III crack propagation is observed for PP while LDPE is a mix mode due to its high ductility and large visible plastic zone. The idealization and testing methods used are consequently proven appropriate.

6.2 Results and Conclusions

- Experimentally tensile tests in fracture Mode I have been performed with different crack shapes; flat, circular and elliptical. A comprehensive and simple numerical procedure for
extraction of continuum material data and damage criterion for initiation and propagation have been presented. This working method shown good results and numerical tests were able to predict experimental tests.

- Material properties extracted from continuum material and material model developed for simulations approved appropriate for tensile and different crack shape tests.
- The experimental stress strain results of thin polymer plates with a different crack shape hole in the centre are showing that theoretical predictions are nearly as valid as experimental results.
- Experimentally, available test methods for trouser tear testing, has been utilized for low extensible and highly extensible thin polymer films successfully with repeatable and reproducible results.
  - Low extensible polymers
    - Constant tearing force and a Mode III crack propagation.
    - Anisotropic material behaviour for PP.
    - No yielding before fracture with high propagation rate.
    - Extremely small tearing force and energy
  - Highly extensible polymers
    - Linearly increasing tearing force and mix mode crack propagation.
    - Complete yielding before fracture slow crack propagation or growth rate.
    - Large plastic deformation and 10 times higher tearing force and energy as shown in Table 3.2.

- Crack propagation or fracture growth rate is very much faster for PP than for LDPE. Molecular orientation of the film is controlling the tear strength of the film. PP film is more oriented towards MD and has higher in plane tear strength.
- Live microscope or video results are very fruitful for deep analysis and better understanding of polymer crack initiation
and growth rate. Zonoscope is an extremely good tool to define different deformation zones for EWF and highlight stress concentrations.

- Simulation results for PP shown a smooth and realistic behaviour in Abaqus/Implicit, while Abaqus/explicit showed quite a shaking and less smooth simulation. Results values are almost similar.
- Material anisotropy is shown with experimental and Scanning electron Microscope (SEM) results. SEM analysis has shown the brittle and ductile film behaviour for PP and LDPE in a realistic way.

### 6.3 Future Work

- Develop the numerical methods for simulating trouser tear testing
- Try to develop some better way to calculate the fracture mechanical material properties of thin films in tearing.
7. References


[27] “Andreasson_TetraPak_final_2242012.pdf.”


Appendix

Appendix A: Trouser Tear Test Physical Test Videos:

For PP, Trouser tear Test video can be watched here,

http://www.youtube.com/watch?v=Nc9KfC08wso

For LDPE, Trouser Tear Test video can be watched here,

http://www.youtube.com/watch?v=sjgxQ6DRhXw

Tensile Test Videos:

Foe Tensile Test of LDPE in different crack shapes under zono scope can be watched here,

http://www.youtube.com/watch?v=9J9YBHudVI&feature=youtu.be
Appendix B: Test results

Figure PP tensile test with 10mm central crack
Figure Tearing PP anisotropically in MD, CD & 45

Figure Simulation Results for Same Fracture Strain and Converging Fracture Strain
Figure Grip regrip (5mm-30mm extension) Trouser Tear Test

MD sharp knife cut crack and self driven cut.

SEM Photos
Figure Aluminum foil after Trouser Tear Test

Figure PP MD crack tip Deformation
Figure Explanation of Higher peaks in CD
Appendix C: Modelling Technique and input parameters in Abaqus

As the abaqus standard point out that when the simulation was done by millimetre, the unit for Young’s modulus should be MPa, the density should be g/mm³, and time should be second.

**Tensile**

**Density:** 0.0009

**Elastic property:**

<table>
<thead>
<tr>
<th>Young’s modulus</th>
<th>Poissons ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>4739.2</td>
<td>0.3</td>
</tr>
</tbody>
</table>

**Ductile damage for circle crack:**

<table>
<thead>
<tr>
<th>Fracture Strain</th>
<th>Stress Triaxiality</th>
<th>Strain Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15</td>
<td>-5</td>
<td>0</td>
</tr>
<tr>
<td>0.15</td>
<td>-5</td>
<td>0</td>
</tr>
</tbody>
</table>

**Ductile damage for Ellipse crack:**

<table>
<thead>
<tr>
<th>Fracture Strain</th>
<th>Stress Triaxiality</th>
<th>Strain Rate</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
<tr>
<td>0.3</td>
<td>-5</td>
<td>0</td>
</tr>
</tbody>
</table>

**Damage evolution:**

**Type:** Displacement

**Softening:** Linear

**Degradation:** Maximum

**Displacement at Failure**
Plastic values for both circle crack simulation and ellipse crack simulation:

<table>
<thead>
<tr>
<th>Yield Stress</th>
<th>Plastic Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.0475</td>
<td>0</td>
</tr>
<tr>
<td>40.2414</td>
<td>0.0021</td>
</tr>
<tr>
<td>50.0698</td>
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<tr>
<td>60.1408</td>
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<td>70.2142</td>
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<td>90.0991</td>
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<td>100.0221</td>
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<td>120.0632</td>
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<td>130.0605</td>
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<tr>
<td>140.129</td>
<td>0.0618</td>
</tr>
<tr>
<td>150.2066</td>
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</tr>
<tr>
<td>160.0876</td>
<td>0.0765</td>
</tr>
<tr>
<td>170.1363</td>
<td>0.0843</td>
</tr>
<tr>
<td>180.1978</td>
<td>0.0924</td>
</tr>
<tr>
<td>190.0231</td>
<td>0.1009</td>
</tr>
</tbody>
</table>
Assembly:

After assigning of the material properties instance of the specimen is created.

Instance type: Independent (mesh on instance)

Step:

A new step is created and assigned the following parameters on the same.

Procedure type: General

Step: Dynamic Explicit

Basic

Time setting for circle crack simulation:

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Nlgeom</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>On</td>
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</tbody>
</table>

Time setting for ellipse crack simulation:

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Nlgeom</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>On</td>
</tr>
</tbody>
</table>
Then set reference point and make constraint for the reference point and the upper edge, the setting should use constraint-coupling-select the point-select the upper edge-done.

Then set amplitudes:

Amplitudes for circle crack simulation:

<table>
<thead>
<tr>
<th>Time/Frequency</th>
<th>Amplitude</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
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</tbody>
</table>

And amplitudes for ellipse crack simulation:

<table>
<thead>
<tr>
<th>Time/Frequency</th>
<th>Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>1</td>
</tr>
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</table>

**Tearing**

**Density**: 0.0009

**Elastic property for CD direction simulation**:

<table>
<thead>
<tr>
<th>Young’s modulus</th>
<th>Poisons ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>46.5</td>
<td>0.3</td>
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</tbody>
</table>

**Elastic property for MD direction simulation**:

<table>
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<tr>
<th>Young’s modulus</th>
<th>Poisons ratio</th>
</tr>
</thead>
<tbody>
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<td>128.9</td>
<td>0.3</td>
</tr>
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</table>

**Ductile damage for CD direction simulation**:

<table>
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<tr>
<th>Fracture Strain</th>
<th>Stress Triaxiality</th>
<th>Strain Rate</th>
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</thead>
<tbody>
<tr>
<td>0.01</td>
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<td>0</td>
</tr>
<tr>
<td>0.01</td>
<td>5</td>
<td>0</td>
</tr>
</tbody>
</table>
Ductile damage for MD direction simulation:

<table>
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<th>Fracture Strain</th>
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<th>Strain Rate</th>
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<tbody>
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<td>-5</td>
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</tr>
<tr>
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<td>5</td>
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</tbody>
</table>

Damage evolution:

Type: Displacement

Softening: Linear

Degradation: Maximum

<table>
<thead>
<tr>
<th>Displacement at Failure</th>
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</thead>
<tbody>
<tr>
<td>0.01</td>
</tr>
</tbody>
</table>

Plastic for CD direction simulation:

<table>
<thead>
<tr>
<th>Yield Stress</th>
<th>Plastic Strain</th>
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<tbody>
<tr>
<td>40</td>
<td>0</td>
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<tr>
<td>20.96</td>
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<td>20.08</td>
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<td>19.68</td>
<td>3.829</td>
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<td>19.64</td>
<td>4.319</td>
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</table>
Plastic for MD direction simulation:

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<td>112.7</td>
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</table>

**Assembly:**

After assigning of the material properties we then create the instance of the specimen.

Instance type: Independent (mesh on instance)

**Step:**

Create a new step 1 and assign the following parameters on the same.

Procedure type: General

Step: Dynamic Explicit

Basic
Interactions:

Here the constraint the two reference points with the respective leg edges, and in constraints coupling the reference point with the edge respective. Then assign an appropriate length of seam crack for the length of leg required.

After that set amplitudes:

Amplitudes for circle crack simulation:

<table>
<thead>
<tr>
<th>Time/Period</th>
<th>Amplitude</th>
</tr>
</thead>
<tbody>
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<td>1</td>
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