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The Effects of Stress Triaxiality on the Neck Initiation and Fracture of High-density Polyethylene (HDPE)

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Abstract

This study analyses the tensile mechanical behaviour and deformation of neck i.e localization initiation, propagation and fracture of injection-moulded polymer composed of high-density polyethylene (HDPE) as a function of initial stress triaxiality. Three different specimen geometries namely i) Simple tension, ii) Plane strain and iii) Shear specimens were punched from injection-moulded HDPE plates and tested experimentally in uniaxial tension to introduce different stress triaxialities. These specimen geometries used are standard for the material characterization of sheet metals. However, for plate polymer materials such specimen geometries have not comprehensively been studied earlier. Standard shear specimen geometry has been further optimized in this work using finite element models to restrict unwanted out-of-plane deformations arising at large deformation. The digital image correlation (DIC) technique is used to acquire the full field deformation and in particular the localized strains in the neck region of the specimens. Based on the major-minor strain paths from DIC-measurements stress triaxiality has been calculated. It is challenging to follow the stochastic pattern at larger local strain in DIC and hence the strain at failure has been measured using orthogonal grid lines on the specimen surface. Finally, strains at neck-initiation and failure at three different stress triaxialities are reported for injection-moulded HDPE in two material orientations. It is observed that within the elastic limit the stress triaxialities obtained from the experimental tests were close to the ideal values found in the literature and neck-initiation strain is strongly dependent on the stress triaxiality. However, as neck initiates and propagates, the triaxialities for all geometries shift closer to the measured value in a simple tension specimen i.e. 0.33 limiting the effect of the initial triaxiality on failure strain.

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1. Introduction

High-density polyethylene (HDPE) is one of the most used polymers in the liquid food packaging industry. During manufacturing, liquid-filling, transportation and storage, a package experiences a wide variety of loading conditions Islam (2019). Finally, opening some packages requires intentional damage and failure in a thin layer of HDPE. In many package designs, part of the package, e.g. package top, is manufactured by injection-moulding. Produced part is a shell-like structure of HDPE plates thinner than 1 mm. During the filling stage in the injection-moulding cycle, material flow velocity into the mould varies largely along the thickness. The cooling rate of HDPE at the core of the mould is slower compared to mould surfaces. Hence, the injection-moulded material can be expected to be anisotropic and inhomogeneous Koon (2018) Fujiyama (1977). The material properties of the HDPE studied in this work are also anisotropic, strain rate dependent and highly ductile reaching engineering strain of more than 10\% - Andersson (2022).

Stress triaxiality, which is a measure of hydrostatic stress normalized by von Mises stress has an effect on neck-initiation and failure strain of many reported metallic cf. Prez (2020) Andrade (2017) and polymeric cf. Bridgman (2013) Ognedal (2014) materials. To study the stress triaxiality effect in polymeric materials, axisymmetric notched tensile specimens are widely used where different notch radius initiates different triaxialities. In Olufsen (2019) 10 mm diameter bars with 2, 5 and 20 mm centre notch radius were used with mineral-filled Polyvinyl chloride (PVC) and the strain field was measured with DIC. Authors reported the three notch radii corresponding to an initial stress triaxiality of 0.4, 0.6 and 0.9, respectively, at the centre of the minimum cross-section. Authors in Ognedal (2014) used axisymmetric tensile bars with the same dimensions as the aforementioned study with the addition of a 0.8 mm notch diameter and used an optical extensometer for strain measurement in PVC and HDPE materials. Similarly, to determine stress triaxiality dependent neck-initiation and fracture behaviour in HDPE cf. G’sell (1983) and Polyether ether ketone (PEEK) cf. Chen (2016), notched bars were used. The effect of triaxiality in plane stress condition in PVC 4 mm thick plate was studied in Selini (2013) with different notch radii in rectangular tensile specimens. Initial stress triaxialities in all above-mentioned works were calculated from specimen geometry features i.e. in a bar, using the smallest radius of the notch and the bar Bridgman (2013) and for plate, notch radius and width of the plate Bai (2007).

The injection-moulded polymeric part in a liquid food package is seldom thicker than 1 mm hence in this study, 0.6 mm thick HDPE plates injection-moulded in the laboratory were cut with a metal tool to produce different test specimen geometries. Smaller thickness restricts the use of bar geometry for inducing different triaxialities. Prez (2020) reported to use geometry ‘A10’, ‘PS’ and ‘S45’ to achieve different stress-triaxialities around uniaxial tension, plane strain and shear loading in nickel-based superalloy plates. Andrade (2017) used compact sized tension, plane strain and shear specimen geometries for the same purpose in dual-phase steels. Further studies are needed before using similar specimen geometries together with highly ductile HDPE which was covered in the current work.

In this article, neck-initiation and failure strain in HDPE plate material were measured. It is important yet tricky to identify the true strain at neck-initiation correctly because of rapid strain localization at post-neck-initiation deformation. Thanks to DIC full-field strain measuring technique that led to the development of several methods to take on this task. Time dependent evaluation method ISO 12004-2, flat valley method proposed by Martinez-Donaire et al. Martinez-Donaire (2014) and a more statistical approach by Sigvant et al. Sigvant (2008) are few of them. An alternative method can be the visual inspection of the existence of any neck-initiation on the DIC measured strain-field. The limitation of DIC technique is apparent close to failure when reliable correlation around the failed area is harder to achieve due to the high distortion of the stochastic pattern.

In this article, the specimen geometries adopted in Andrade (2017) were further modified and used to study stress triaxiality in HDPE in two material orientations. Neck-initiation strain at different stress triaxialities were measured using time-dependent method and reported. Finally, the challenge of measuring very large strains at failure in HDPE was addressed and failure strains were reported. The findings are discussed with some concluding remarks in the final section.
2. Experiments

2.1. Material description

The test specimens were punched out in the melt flow direction, in this work referred to as the machine direction (MD) and the transverse to melt flow direction referred to as cross direction (CD) from injection-moulded HDPE plates visible in Fig. 1 (c). The studied HDPE has a density of 0.95 g/cm³ and a meltflow index of 2.6 g/min. Plates were produced in accordance with ISO 294-5, the moulding settings can be found in Table 1. Table 2 presents the basic properties of the studied material in MD and CD obtained using uniaxial tensile testing according to ISO 527-2-1BA with full-field strain measurement from 2D digital image correlation (DIC).

Table 1. Injection-moulding settings.

<table>
<thead>
<tr>
<th>Setting</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shot volume [ccm]</td>
<td>11</td>
</tr>
<tr>
<td>Hold pressure 1 [bar]</td>
<td>1000</td>
</tr>
<tr>
<td>Hold pressure 2 [bar]</td>
<td>750</td>
</tr>
<tr>
<td>Melt temperature [°C]</td>
<td>260</td>
</tr>
<tr>
<td>Mold temperature [°C]</td>
<td>60</td>
</tr>
<tr>
<td>Nozzle temperature [°C]</td>
<td>255</td>
</tr>
</tbody>
</table>

Table 2. Basic material properties of the tested HDPE.

<table>
<thead>
<tr>
<th>Orientation</th>
<th>E Modulus (E) [MPa]</th>
<th>Poisson’s ratio (ν) [-]</th>
<th>Yield stress (σy) [MPa]</th>
<th>Lankford coefficient (r) [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD</td>
<td>515</td>
<td>0.33</td>
<td>10</td>
<td>0.49</td>
</tr>
<tr>
<td>CD</td>
<td>551</td>
<td>0.49</td>
<td>10</td>
<td>0.73</td>
</tr>
</tbody>
</table>

Fig. 1. (a) Specimen geometries; (b) cutting die and (c) material orientations.
2.2. Design of specimens for stress triaxiality tests

A HDPE dogbone tensile specimen cut from an injection-moulded plate under uniaxial tension shows very large deformation beyond the initial yield limit. During such a test, specimen would deform locally after neck-initiation and develop a small region of stable neck around it. Subsequent loading would not cause the stable neck region to fail, instead, adjacent material to the neck is pulled and added to the initial neck. This ‘chewing gum’ like behaviour causes a very long stable neck until failure. The longitudinal engineering strain value in the neck region can reach 10 \[-\]. It poses a challenge to design a set of specimen geometries that can induce different stress triaxialities in HDPE plates under tension. Researchers has tested sheet metal plates for measuring stress triaxiality dependent failure properties for low to medium ductile metals as mentioned in section 1.

![Fig. 2. (a) Optimized HDPE hardening curve (normalized); (b) Stress triaxiality in FE-model for three chosen specimen geometries.](image)

Compact sized tension (A10), plane strain (PS) and shear (SH) specimen geometry used by Andrade (2017) were taken as reference geometries to test and improve for use with HDPE. In this work, shear (SH) specimen geometry was further modified using finite element simulations to adopt HDPE’s very high ductile behaviour. The simulation models in Abaqus (2021) used isotropic hardening and von Mises yield criterion. It was very important to accurately model the hardening of the material to capture the ‘chewing gum’ like behaviour in HDPE described earlier and it was done in MD of the material. To make stable necking as experienced in physical testing possible, in FE-simulations, the material hardening curve slope initially should decrease gradually but beyond stable-neck-strain increases instead. Such behaviour of the hardening curve was captured with the hardening curve shape presented in Fig. 2 (a). Six parameters were optimized in Abaqus Insight (2020) against experimental force-displacement response that defined this hardening curve shape. The optimization scheme used can be found in the work by Wahlström (2018).

Several versions of the specimen, especially, the shear specimen were tested first in FE-models and later with physical testing before reaching the geometries presented in Fig. 1. The Fig. 2 (b) shows the simulated triaxiality values at the centre point of the necking region obtained using the final geometry. The triaxiality in all cases increased with increase in strain. It worth mentioning that in A10 and PS, stress triaxiality values are not constant over the width of the specimens instead form a parabola along the width with maximum triaxiality at the centre. This behaviour for A10 is depicted in Fig. 2 (b).

2.3. Testing method

The specimens of the designed geometry were cut from injection-moulded plates in MD and CD using cutting dies as shown in Fig. 1. The test matrix is presented in Table 3 where three acceptable repetitions of tensile tests were performed for each geometry in MD and CD, both with stochastic spray paint pattern on the surface for DIC strain measurements and with hand-drawn grid lines for large strain measurements. As the material is close to white...
in colour, only one layer of black spray paint was used to create the stochastic patterns. The test speed was 20 mm/min in an MTS QTest 100 tensile test machine with 100 N loadcell and hydraulic grips. It is worth mentioning that full-field strain measurement of DIC is excellent for identifying neck-initiation strain but at very large strains that HDPE specimens experience, correlation of the DIC fails to follow the deformations. Tests with grid lines helped to digitally measure the deformations between lines to estimate strain up to failure.

Table 3. Test matrix.

<table>
<thead>
<tr>
<th>Orientation / Tests</th>
<th>A10</th>
<th>PS</th>
<th>SH</th>
<th>DIC</th>
<th>Grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD</td>
<td>3 / 3</td>
<td>3 / 3</td>
<td>3 / 3</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>CD</td>
<td>3 / 3</td>
<td>3 / 3</td>
<td>3 / 3</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

3. Results and Analysis

3.1. Test measurements

Force and displacement responses were recorded for all tests; Fig. 3 shows the responses for three individual tests in all cases and their respective average curves. Out-of-plane rotation of the shear specimen (SH) that is caused by lower stiffness and large deformation was limited in the newly designed shear specimen, however, was not completely avoided. A significant spread of the shear force displacement response was observed, especially in MD, which can be linked to the inconsistency in the level of out-of-plane rotation. The deformations in the tests with the stochastic pattern were video recorded and analyzed in 2D GOM Correlate. Fig. 4 illustrates the evolution of true major strain (True maximum principal strain) and strain rate in the A10 specimen at a point in the centre of the initial neck; for both MD and CD material orientations. It was clear from the full-field strain evolution that the neck initiates at an early stage of loading. Point (1) in each case is the neck-initiation stage and point (2) is where the strain rate at the neck reaches its maximum as can be seen in Fig. 4. Few more subsequent deformations and corresponding strain and strain rates are highlighted in points (3) and (4). It was found that DIC correlation was able to track deformation up to a very large strain before failure. If one investigates the reason and closely observes, it would be evident that the neck in HDPE A10 is very stable i.e. strain localizes and forms neck but under subsequent loading, strain rate decreases in the initial neck and pulls material from the nu-necked region. This is visible in the strain rate plots in Fig. 4 which decreases close to zero at large strain. Worth repeating that the point where the strain/ rate was measured was centred at the initial neck material. These facts enable the initial spray paint pattern to be visible at large strain helping the DIC analysis. The effect of the HDPE anisotropy can be seen in the neck-initiation strain and deformation by visual comparison from Fig. 4.

Full-field true major and minor strains can be analyzed to study strain evolution and visually identify neck-initiation strain in A10, PS and SH. Additionally, these two strain components and their rate at the centre point of the initial neck were recorded for all three specimen geometries in order to identify the neck-initiation strain and stress triaxiality respectively. Sample strain paths are plotted in Fig. 5 with highlighted neck-initiation points. These paths in MD and CD showed deviation due to material anisotropy which is also reflected in different Lankford coefficients. Noticeably, the flat nature of the strain path in MD SH in Fig. 5 is a direct consequence of out-of-plane rotation in the shear specimen that DIC detects as minor strain in the initial measurements. The location of the initial-neck formation varied among different repetitions for the same specimen geometry.

The test deformations from those with grid lines were also video recorded. A digital scale was used on the images from the videos to measure the distance between grid lines around the neck at multiple times/deformation stages. This provided discrete local strain measurements up to the failure of the specimens. Measurement of shear strains was particularly challenging due to two reasons. One is the out-of-plane rotation of the specimen when loaded and another reason is that the strains in the neck are not purely shear in nature but dominated by tension. Measuring the shear strains by measuring the shear angle in the grid also posed a challenge but was tackled by measuring angles digitally.
from the test videos. The measurements from grid tests are still believed to be accurate within reasons. Deformation images at 3 stages up to failure for three sample specimen geometries are presented in Fig. 7 (c)

3.2. Transformation of strain path to stress triaxiality

Stress triaxiality is defined as the ratio of the mean stress $\sigma_m$ and the von Mises equivalent stress $\sigma_{eq}$ as presented in Eq. 1. It is more convenient to measure strains and transform those to stress triaxiality with yield criterion of choice. To transform DIC measured strain paths from different test geometries into stress triaxiality, Eq. 2-6 were employed.
similar to the approach adopted by Rickhey (2022). Eq. 4 was used to transform the major-minor strain path to stress triaxiality according to the von Mises yield criterion and Eq. 6 was used for the same transformation according to the Hill48 yield criterion. Here, \(\epsilon_1, \epsilon_2\) are major and minor true strain and \(\dot{\epsilon}\) denotes strain rates. Lankford coefficients \(r_0\) and \(r_{90}\) are those reported in MD and CD in Table 2. Eq. 6 reduces to Eq. 4 for isotropic material when \(r_0\) and \(r_{90}\) are equal to 1.

\[
\eta = \frac{\sigma_m}{\sigma_{eq}} \quad (1)
\]

\[
\beta = \frac{\epsilon_2}{\epsilon_1} \quad (2)
\]

\[
\beta' = \frac{\dot{\epsilon}_2}{\dot{\epsilon}_1} \quad (3)
\]

\[
\eta = \frac{1+\beta'}{\sqrt{3(1+\beta')^{\frac{1}{2}}}} \quad (4)
\]

\[
\alpha = \frac{\beta' + \frac{1}{\gamma} - 1}{\gamma + 1 + \beta'} \quad (5)
\]

\[
\eta = \frac{1+\alpha}{3 \sqrt{3(1+\gamma)\alpha + \frac{1}{\gamma}(1+\gamma)\alpha^2}} \quad (6)
\]

The effect of anisotropy is visible in the calculated stress triaxiality using these two yield criteria conversion in Fig. 6 (b). Comparing triaxiality values between MD and CD, one observes that in CD, attained a range of triaxiality for the chosen geometries is lower than in MD. A significant difference is observed in the shear loading.

3.3. Limit strains

Two limit strains i.e. neck-initiation strain and failure strain were measured in the studied HDPE at different triaxialities which are presented in Table 4. Necking or strain localization begins quite early compared to the total deformation in the specimens. DIC full-field strain measuring technique led to the development of several methods to identify the neck-initiation strain. One of them, the time dependent evaluation method as employed by authors in Hora (2012) was used to identify neck-initiation in this study. This evaluation method is based on a trend analysis of the strain rate in the area of necking and subsequent failure. Here, first, a region of a sharp increase in major strain rate is identified. Two approximate tangents in the strain rate curve is then drawn on each side of the sharp strain rate...
change. The meeting point of these two tangent lines is then identified as the neck-initiation stage/time and the major strain at that stage/time is accepted as neck-initiation strain. An example of such detection for A10, CD is presented in Fig. 6 (a).

Alternatively, studying the major strain field in DIC deformation stages also helps identify neck-initiation. From the comparison of these two methods, it was found in this study that initial-necking is detected earlier using time dependent method compared to visual inspection. For comparison, in MD of A10, test-1 neck-initiation strain measured by time dependent method was 0.62 whereas the same measured by visual inspection of full-field strain

Fig. 6. (a) Time dependent method as used in A10 CD; (b) Neck-initiation strain at triaxiality calculated using von Mises and Hill48 yield criteria.

Fig. 7. Failure strain measurements. (a) True major strain evolution measured from grid deformation (b) True major failure strain in A10, PS and SH; in MD and CD (c) Grid marks and deformation at different loading stages.
was 0.65. Fig. 6 (b) shows that in CD, neck-initiation strain gradually decreases with an increase in stress triaxiality. On the contrary in MD, maximum neck-initiation strain is in the intermediate triaxiality from A10 test.

Fig. 7 (a) presents the discrete strain measurements from grid line tests up to failure for one specimen each for different geometries and material orientations. Failure strain and their spread for the same is depicted in Fig. 7 (b). HDPE tend to fail at very high true strain in A10 and PS. Shear strain at failure measured from distortion of grid angle of SH was significantly lower. Stress triaxiality changes with increased strain in all cases. Especially, beyond the initial neck up to failure, the triaxiality value gradually shifts towards 0.33 expected from uniaxial-loading. Hence the failure strains can not be linked to initial triaxiality in the specimens. Moreover, due to this shift towards uniaxial loading, the failure strains in A10 and PS are similar in magnitude but neck-initiation strain for them are significantly different as can be seen in Table 4. This can be concluded from the observations that neck-initiation strain is strongly stress triaxiality dependent in HDPE plates and failure strain is not.

4. Conclusions

An experimental method and modified specimen geometries were presented for measuring neck-initiation and failure strains at different stress triaxialities in injection-moulded HDPE plates. A range of stress triaxiality was induced in the material using three different specimen geometries called ‘A10’, ‘PS’ and ‘SH’. Triaxiality levels were quantified from true major-minor strain path measurements of DIC at the centre of the initial neck with the help of von Mises and Hill48 yield criteria. It was found that neck-initiation strains are different at different stress triaxialities and are not the same in machine and cross directions of HDPE i.e. anisotropic. However, beyond neck-initiation, strain paths from all geometries shift towards uniaxial tension which indicated that the failure strain is not strongly dependent on initial stress triaxiality. For the large failure strain measurements, grid lines on the specimen surface were successfully employed in a combination with video recording and image analysis of the deformed lines. All measured stress triaxialities, neck-initiation and failure strains were reported in MD and CD orientations for the studied HDPE material.

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