Behaviour of PVC and HDPE under highly triaxial stress states: an experimental and numerical study

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Abstract

This paper addresses the deformation of axisymmetric tensile bars, made of mineral-filled PVC and HDPE, with and without pre-machined notch. The purpose of the study is both to investigate the mechanical behaviour under various stress triaxialities, induced by different notch radii, and the capabilities of a phenomenological constitutive model. The yield stress and the plastic dilation have been chosen as the key response parameters from the tests in order to evaluate the yield function and the flow potential of the constitutive model. It is found that the yield stress and the plastic dilation of the mineral-filled PVC are highly sensitive to hydrostatic pressure. The yield stress of the HDPE hardly changes, while the plastic dilation increases with increasing stress triaxiality. The experimentally observed plastic dilation of both materials is related to void growth. The constitutive model reproduces force-displacement relationships for both materials with reasonable accuracy. However, the numerical simulations underestimate the plastic dilation for high stress triaxialities.

Keywords: Polymer, Stress Triaxiality, Pressure Sensitivity, Plastic Dilation, Void, Constitutive Model

# Introduction

Many polymers have a mechanical response that is sensitive to the hydrostatic stress. This can easily be observed from uniaxial tension and compression tests where the yield stress often is found to be higher in compression than in tension. In more general terms it can be stated that the yield stress changes with the hydrostatic stress component. Moreover, plastic dilation on the macroscopic scale is commonly observed in polymeric materials. The dilation often has its origin in damage such as crazing, particle debonding or void growth on the microscopic scale. These mechanisms also depend on the stress state.

A tension-dominated triaxial stress state can be produced by employing axisymmetric tensile bars with a pre-machined notch. This geometry is known to create a triaxial stress state by introducing transverse components to the stress tensor. The smaller the radius of the pre-machined notch, the higher is the stress triaxiality in the specimen.

During experimental testing of metallic samples it is common to work under the assumption of isochoric plastic deformations. In the case of metallic axisymmetric specimens it is therefore adequate to measure the contraction of the minimum cross section of the notch to determine the axial strain. In polymers exhibiting plastic dilation another instrumentation protocol is needed because measurements of both the transverse and the axial deformation are required.

Experiments on axisymmetric tensile bars made of polymers are found in the literature ([Boisot et al., 2011](#_ENREF_2" \o "Boisot, 2011 #153); [Castagnet and Deburck, 2007](#_ENREF_5" \o "Castagnet, 2007 #155); [Challier et al., 2006](#_ENREF_7" \o "Challier, 2006 #55); [Laiarinandrasana et al., 2009](#_ENREF_13" \o "Laiarinandrasana, 2009 #154)). Castagnet and Deburck ([2007](#_ENREF_5" \o "Castagnet, 2007 #155)) measured the minimum cross section diameter during deformation by employing a charge-coupled device (CCD) to follow deformation of a black line drawn around the minimum cross section of their translucent samples. They used the diameter reduction as an indicator of the evolution of voids. The change of the axial length of the notched part of the specimen was used to compute axial strains. By plotting the radial strain against axial strain for specimens with different radii, they showed that the change of the diameter, i.e. the radial strain, was lower for higher triaxialities. Also Boisot et al. ([2011](#_ENREF_2" \o "Boisot, 2011 #153)) plotted radial strain against axial strain in order to express how the volume change was affected by stress triaxiality. They measured the reduction of the minimum diameter of polymer specimens by applying a strain gauge at the root of the notch. Similar measurements have been performed by [Challier et al. (2006)](#_ENREF_7" \o "Challier, 2006 #55) and [Laiarinandrasana et al. (2009)](#_ENREF_13" \o "Laiarinandrasana, 2009 #154). Moreover, Boisot et al. ([2011](#_ENREF_2" \o "Boisot, 2011 #153)) used a scanning electron microscope (SEM) to observe test specimens from interrupted tests and to determine the porosity of the deformed material in the notch.

In the study presented in this paper a CCD camera was employed to capture the deformation of the notch as the specimen extended. Both the external contour of the notch and the displacement of two extensometer markers, painted on the specimen, were monitored during the test. Thus, the relevant strain measures of the deformation could be calculated during post-processing of the digital images.

Two different thermoplastics are addressed: PVC (polyvinyl-chloride) and HDPE (high density polyethylene). The PVC is an amorphous thermoplastic filled with a volume fraction of particles of about 0.2 ([Ognedal et al., 2014](#_ENREF_18" \o "Ognedal, 2014 #220)). The HDPE is a semicrystalline thermoplastic that contains considerably fewer particles. Results from uniaxial tension and compression tests have earlier suggested that the PVC is highly pressure sensitive both with respect to yield stress and plastic dilation ([Moura et al., 2010](#_ENREF_16" \o "Moura, 2010 #61)). The macroscopic dilation in the PVC is a result of microscopic void growth ([Ognedal et al., 2014](#_ENREF_18" \o "Ognedal, 2014 #220)). For the HDPE, on the other hand, the yield stress in tension and compression is equal. Moreover, the plastic dilation in a uniaxial stress state is minor in the HDPE. However, holes started to grow in the centre of HDPE specimens subjected to biaxial tension ([Ognedal et al., 2012](#_ENREF_19" \o "Ognedal, 2012 #215)). This observation indicates that higher stress triaxialities may trigger some damage mechanism.

As a consequence of the commonly observed difference between the yield stress in tension and compression, material models with a pressure sensitive yield criterion as well as a pressure sensitive flow potential for polymer materials are often employed. [Polanco-Loria et al. (2010)](#_ENREF_20" \o "Polanco-Loria, 2010 #11) proposed such a model intended for large-scale finite element analysis of thermoplastics. Since the development of this phenomenological model had industrial applications in mind, the simple one-parameter Raghava function ([Raghava et al., 1973](#_ENREF_21" \o "Raghava, 1973 #88); [Raghava and Caddell, 1973](#_ENREF_22" \o "Raghava, 1973 #72)) was chosen for the yield criterion as well as in the non-associated plastic potential function. Thus, plastic dilation from damage evolution is incorporated simply as the volume change that is given by the gradient of the plastic potential. The material model captures the main features of the behaviour at the moderate stress triaxialities in biaxial tension ([Ognedal et al., 2012](#_ENREF_19" \o "Ognedal, 2012 #215)). However, the model has not yet been evaluated for higher stress triaxialities.

Homogenized micromechanical models, like different versions of the model originally proposed by Gurson ([1977](#_ENREF_10" \o "Gurson, 1977 #36)), can describe the damage behaviour of ductile materials by nucleation, growth and coalescence of micro-voids. Such models have successfully been used in applications where void growth is promoted by high stress triaxialities, see e.g. [Challier et al. (2006)](#_ENREF_7" \o "Challier, 2006 #55) or [Boisot et al. (2011)](#_ENREF_2" \o "Boisot, 2011 #153). The drawback of these models is the complicated parameter identification process. For instance, information about initial void volume fraction is needed. This calls for somewhat sophisticated test equipment, seldom found in industry laboratories. It is therefore interesting to investigate the limitations of the phenomenological model proposed by [Polanco-Loria et al. (2010)](#_ENREF_20" \o "Polanco-Loria, 2010 #11) which was designed in a such way that all material parameters can be determined from uniaxial tests in tension and compression.

The discussion above can be summed up by the questions:

* What is the behaviour of the PVC and the HDPE at high triaxial stress states with respect to yielding, flow and damage evolution?
* Is the hyperelastic-viscoplastic material model proposed by [Polanco-Loria et al. (2010)](#_ENREF_20" \o "Polanco-Loria, 2010 #11) capable of predicting the behaviour of these two materials at high stress triaxiality?

The main objective of this study is two answer these two questions. The paper is organized as follows: First, the materials and the setup for the experimental part of the study are addressed in Section 2. A brief numerical study of the distribution of stress triaxiality at onset of yielding in the test specimens with different notch radii follows in Section 3. Thereafter, Section 4 presents the results from the laboratory tests. Photos of fracture surfaces from representative tests are included in this section. The numerical model, incorporating a description of the constitutive material model ([Polanco-Loria et al., 2010](#_ENREF_20" \o "Polanco-Loria, 2010 #11)), is addressed in Section 5. Subsequently, the results from the numerical simulations are presented in Section 6. Discussions and conclusion follow in Section 7 and Section 8.

# Materials and experimental method

## Materials

This study concerns two fundamentally different thermoplastics: an amorphous PVC and a semicrystalline HDPE. Both materials were acquired as 10 mm thick extruded sheets from the supplier SIMONA. Although [Moura et al. (2010)](#_ENREF_16" \o "Moura, 2010 #61) found a slight direction dependency regarding the mechanical behaviour, good results have been obtained when isotropy is assumed ([Moura et al., 2010](#_ENREF_16" \o "Moura, 2010 #61); [Ognedal et al., 2012](#_ENREF_19" \o "Ognedal, 2012 #215)). Both materials will therefore be treated as isotropic in this study.

The yield stress of the PVC is higher in compression than in tension by a factor of 1.3 ([Hovden, 2010](#_ENREF_12" \o "Hovden, 2010 #87)). Stress whitening is clearly observed at onset of plasticity. Moreover, [Ognedal et al. (2014)](#_ENREF_18" \o "Ognedal, 2014 #220) observed macroscopic plastic dilation during uniaxial deformation due to particle debonding and void growth. They also found from SEM investigations that the PVC contains a volume fraction of mineral particles of about 0.2.

No difference was observed in the yield stress in tension and compression of the HDPE ([Hovden, 2010](#_ENREF_12" \o "Hovden, 2010 #87); [Moura et al., 2010](#_ENREF_16" \o "Moura, 2010 #61)). Moreover, hardly any volume change was found in uniaxial tension tests. Some particles were identified in a SEM investigation of the HDPE ([Ognedal, 2012](#_ENREF_17" \o "Ognedal, 2012 #185)), however, much less than in the PVC.

SEM micrographs of undeformed PVC and HDPE are shown in Figure 1 a) and b), respectively. From termograviometric analysis it was found that the PVC and the HDPE contain in turn about 45 wt% and 10 wt% solid filler ([Ognedal, 2012](#_ENREF_17" \o "Ognedal, 2012 #185)).

## Experimental setup

The axisymmetric tensile bars were prepared on a lathe according to Figure 2. The material was taken from the 10 mm thick extruded plates of PVC and HDPE. The samples were machined with their longitudinal direction in the extrusion direction. Figure 2 a) shows the geometry of the notched specimens. Four different notch radii  of 20 mm, 5 mm, 2 mm and 0.8 mm were employed. In addition some smooth specimens were machined according to Figure 2 b). Both ends of the specimens had M10 threads for mounting in the tensile machine. The different test specimens will in the following be identified by the material and the initial notch radius , e.g. PVC-08 and HDPE-20. The geometries of all samples are compared in Figure 3.

All specimens were deformed by the same cross-head speed of 0.04 mm/s. The deformation of the notch was surveyed by a CCD camera. The acquisition frequency for PVC-2 and PVC-08 was 2 s-1. For all other tests it was 1 s-1. Each test series was carried out with three replicates. For each geometry and material, the test having the highest image quality from the CCD camera was chosen as the representative one of the three replicates. All specimens made of PVC were deformed until fracture. Regarding the specimens of HDPE, only the samples with the two smallest initial notch radii , i.e. HDPE-2 and HDPE-08, fractured during testing. For all test series, the scatter in the displacement at fracture for the three replicates was minor.

## Stress and strain measurements

Prior to the tests of all notched specimens, four small markers were painted along the notch, see Figure 4 a). The distance between the markers was initially ~ 2 mm. Figure 4 a) also addresses the initial notch radius  and the initial sample diameter . The deformation of the specimens was monitored by a CCD camera. The markers were captured by the camera, facilitating an optical extensometer so that the longitudinal deformation could be followed, see Figure 4 b). In order to obtain clear images of the contour of the specimens, they were placed in front of a background having a contrasting colour. Moreover, the focus of the camera was at the outer edge of the notch. This was important to obtain good tracing of the contour of the specimen, and to find the specimen radius  by image processing after the test.

The minimum specimen radius , the distance  between the optical extensometer markers and the contour of the specimen between the markers were found for each image by use of a MATLAB script created for the purpose by [Dahlen (2011)](#_ENREF_9" \o "Dahlen, 2011 #163). Also the curvature of the contour of the specimen was found by the same MATLAB script. After some deformation a local neck could appear inside the notch, see Figure 4 b). However, by using the traced contour of the specimen, the location of the narrowest cross section with the smallest diameter of the specimen, , was found. Moreover, the volume  between the two extensometer markers was found from revolving the curve describing the left contour around the specimen axis and thereafter calculating the volume of the solid of revolution by disk integration.

As will be demonstrated in Section 3, the stress state in the cross section of the notched samples is inhomogeneous. The average axial stress  is defined as the applied force  over the current minimum cross section area :



It is seen in Figure 4 that the specimen cross section varies over the length . The strain distribution is therefore inhomogeneous over . The average axial strain , based on the displacement of the two extensometer markers, was computed as



The average radial strain  in the section with minimum area was calculated as



Finally, the average volume strain  between the two markers was expressed as



where  is the volume between the two markers for the undeformed sample.

The smooth specimens were marked with multiple extensometer markers at a 2 mm interval in the longitudinal direction. The axial stress and the axial strain were computed according to Equation and Equation also for these specimens.

# Stress triaxiality distribution – numerical study

The shape of the notched tensile bars introduces transverse components to the stress tensor and creates thus a triaxial stress field. Different notch radii  cause different magnitudes of stress triaxiality. Moreover, the stress triaxiality varies with the radial distance from the centre axis of the specimen. The radial distributions of the stress triaxiality in the different specimens in this study were found from finite element simulations at small deformations. The simulations were carried out for the elastic domain to evaluate the stress state, in terms of stress triaxiality, at onset of yielding.

Figure 3 b) to Figure 3 e) display the sketches used to create meshes of axisymmetric solids from 2D-elements. Four-node axisymmetric elements with reduced integration together with a stiffness-based hourglass control were employed to carry out the simulations ([LS-DYNA, 2007](#_ENREF_15" \o "LS-DYNA, 2007 #33)). The notched regions of the specimens were defined by smaller elements, as seen in Figure 5. This was done so that the same meshes could be used in the second part of this study, addressing numerical simulations of the laboratory tests. The part of the sample located between the central markers at Figure 4 a), i.e. 1 mm to each side of the minimum cross section, was divided into 40 elements in the longitudinal direction, while 20 elements were applied in the radial direction.

The simulations were carried out employing elastic material models with Young’s modulus and Poisson’s ratios for the two materials; = 3000 MPa and  = 0.3 for PVC, and = 800 MPa and = 0.4 for HDPE ([Hovden, 2010](#_ENREF_12" \o "Hovden, 2010 #87)).

The stress triaxiality is often represented as the dimensionless stress triaxiality ratio . It is defined as ([Hancock and Mackenzie, 1976](#_ENREF_11))



The definition involves the first stress invariant  and the second deviatoric stress invariant , where  is the Cauchy stress tensor,  is the deviatoric stress tensor and  is the second order unit tensor. According to the above definition a uniaxial stress state in tension gives  while a purely hydrostatic stress state in tension gives an infinitely high stress triaxiality ratio.

The stress state was taken from each of the 20 elements through the minimum cross sections of the axisymmetric meshes. Thereafter, the radial distribution of stress triaxiality ratio  defined in Equation was found for each of the numerical models, see   
Figure 6. The radial distributions spans from = 0 to = 3 mm. It is seen that a smaller notch radius  creates higher stress triaxiality. It can be noted that the radial distribution of  is less homogenous for the specimens with the smallest notch radii. Most of the specimens have the highest stress triaxiality at the centre axis, i.e. at  0 mm. However, this is not the case for the specimen with 0.8 mm, where the maximum  occurs approximately 1.7 mm from the centre.

# Results from experimental tests

## Yield stress

Force-displacement relationships for the three PVC specimens of each geometry are displayed by the solid lines in Figure 7. The reproducibility of the force-displacement response appears to be good. The displacement at fracture was almost similar for the replicates of each notched sample, while the scatter was larger for the smooth specimen. It can be noted that there is not much difference in the maximum force level between the notched PVC specimens of different geometry. The solid lines in Figure 8 show the force-displacement curves for the HDPE specimens. Again, all three specimens of each geometry are included indicating that the repeatability is good also for this material. The major exception is one of the HDPE-20 specimens which reaches a considerably lower maximum force than the other specimens of the same geometry. The general trend is that the level of maximum force for the HDPE specimens increases with decreasing .

The average axial stress  is plotted against average axial strain  in Figure 9 a) for the PVC specimens. The results for one representative sample of each type are presented in the figure. Also the result from a smooth specimen is included to serve as a reference. All stress-strain curves for the PVC specimens have a more or less similar response; the initially linear elastic behaviour is followed by a local stress maximum before softening and strain re-hardening. It is seen that the notched specimens obtain a higher peak stress than the smooth specimen. However, the difference in peak stress between the notched specimens is minor. Figure 10 a) displays the average axial stress plotted against average axial strain for HDPE specimens. The two specimens with the smallest notch radius, i.e. HDPE-2 and HDPE-08, have a softening behaviour after peak stress. These specimens fractured during testing. The other HDPE specimens strain-harden monotonically throughout the deformation and the tests were aborted before fracture.

The rates of average axial strain at maximum force are listed in Table 1. The rate  is found by numerical differentiation of the average axial strain found with Equation . It can be noted that the notched specimens obtained a higher rate of average strain than the smooth specimens. This difference is more evident for PVC than for HDPE. Further, it is seen that all notched specimens have strain rate of order 0.01 s-1.

The test and post-processing methods used in this study were found suitable for the notched bars, where the location for onset of necking is defined by the specimen geometry. However, the method produced poor results for the smooth specimens since onset of necking could not be controlled to occur exactly between two optical extensometer markers. The smooth specimens will not be included in the results hereafter.

## Dilation

The average volume strains  are plotted in Figure 11 a) and b) for PVC and HDPE respectively. The general observation is that the volume change is larger for the specimens with smaller initial notch radius . Thus, it can be stated that the dilation increases quite radically with the stress triaxiality.

The plots of average radial strain  in Figure 12 a) and Figure 13 a) once again demonstrate the increase in volume strain with decreasing . The results show that a small initial notch radius  causes less contraction of the specimen than a large initial notch radius does. Reduced contraction is interpreted as higher dilation. The slopes of the curves for HDPE-20 and HDPE-5 exceed 0.5. This is an effect of  being a measure over the localized zone while  is not. None of the PVC specimens has a slope close to 0.5.

## Fracture

All PVC specimens fractured during testing. Fracture surfaces of representative samples of each of the specimen geometries are displayed in Figure 14. Only the two HDPE specimens with smallest  ruptured in the tests. Again considering representative samples, their fracture surfaces are presented in Figure 15. All fracture surfaces indicate that the failure is dominated by void growth. Small holes can be seen at the PVC fracture surface. Traces after large voids are present at the HDPE fracture surfaces. For both materials, and especially for the HDPE, a fibrillar structure oriented radially outwards in the voids is observed.

Visual observation of the fracture surfaces of the PVC specimens reveals a rough topography. An impression from comparing the different PVC specimens is that a larger initial notch radius, , caused a rougher fracture surface. In general, the topography appears to be rougher in PVC than in HDPE. Comparing the strains at fracture, they were much lower for PVC than for HDPE.

The structure of the fracture surface of HDPE-2 indicates that the voids were relatively large at fracture of this specimen compared to HDPE-08. This is seen from Figure 15 a) and b). The figure also shows that a larger number of voids were present in the HDPE-08 at fracture.

The voids located close to, but not at, the rim of the fracture surface of HDPE-08 also appear somewhat larger than those in the centre and those at the rim. The comparatively large voids are thus in the region of highest triaxiality in the elastic domain, as reported in Figure 6.

It was also noted that some kind of a thin skin layer was formed around the fracture surface of the HDPE specimens. It is not known whether this was a structural or a damage effect, or if it was an effect from machining of the specimens. The specimens were cooled during lathing to avoid material changes due to high temperatures. Nevertheless this might originate from changes in the surface material during machining of the specimens.

# Numerical study

## Numerical discretization and boundary conditions

The five meshes that first were used for simulations of the elastic deformation and evaluation of the stress triaxiality, see Section 3, were also applied for simulations of the experimental tests. All simulations were carried out explicitly in the finite element code LS-DYNA. Mass scaling by a factor of 106 was used to reduce the simulation time. After the simulations it was controlled that the hourglass energy and the kinetic energy were much less than 1% of the total energy. The part of the sample located less than 1 mm to each side of the minimum cross section was represented by smaller elements, as seen in Figure5, to handle the large deformations that were observed in the experiments. The height of this region corresponds approximately to the measure  and hence the distance used for determination of the average axial strain  from the laboratory tests.

The nodes facing the positive and negative *z*-direction at each end of the finite element model were given a prescribed motion of 0.02 mm/s in the direction they were facing. Prediction of failure was not included in the numerical study. When the global displacement in the numerical simulations had passed about 1/3 of the global displacement at fracture in the experiments, the simulations were stopped. Numerical simulations of the specimens that did not fracture were carried out to approximately the same global deformation level as in the experiments.

## Material model

A hyperelastic-viscoplastic material model proposed by Polanco-Loria et al. ([2010](#_ENREF_20)) is applied in this study. The model consists of two parts, Part A and Part B, in order to describe the resistance from two different mechanisms: A) an intermolecular barrier and B) an entropic stiffness due to orientation of molecular network ([Boyce, 2000](#_ENREF_3" \o "Boyce, 2000 #37)). Thus, Part A describes the intermolecular resistance to deformation of the polymer material. It is represented with a hyperelastic-viscoplastic model. Part B takes the network stretching of the molecules, i.e. the entropic part of the response, into account through a hyperelastic formulation. The total Cauchy stress tensor  in the model is taken as the sum of the stress contributions from the two parts



The main kinematic variable in the model is the deformation gradient . It is assumed to be equal for Part A and Part B, i.e. . It follows that the volume change, given as the determinant of the deformation gradient, is the same for the two parts: .

The deformation gradient of the hyperelastic-viscoplastic Part A is decomposed into elastic and plastic contributions, i.e. . The decomposition produces three configurations: a reference configuration , a virtual, intermediate configuration, , and a current configuration . The intermediate configuration, defined by the plastic part of the deformation gradient, , is invariant to the rigid body rotations of the current configuration. The evolution of the intermediate configuration is defined by the differential equation , where  is the plastic velocity gradient with respect to the intermediate configuration.

A Neo-Hookean model is used to allow for large elastic deformations in Part A



where  is the Kirchhoff stress tensor,  is the elastic part of the Jacobian,  is the second-order unit tensor, and  is the elastic left Cauchy-Green deformation tensor. The elastic response is defined by the Lamé constants  and . It can also be expressed by Young’s modulus  and Poisson’s ratio .

The viscoplastic contribution of Part A is computed on the intermediate configuration, , applying the Mandel stress tensor . The relationships between the Kirchhoff and Mandel stress tensors read  and . The Mandel stress tensor is symmetric due to the assumed isotropy of the material. The yield criterion is formulated as



where  is the yield stress in uniaxial tension and  is an isotropic hardening or softening variable. The Raghava equivalent stress  is used to express pressure dependency ([Raghava et al., 1973](#_ENREF_21" \o "Raghava, 1973 #88))



where  and  are respectively invariants of the Mandel stress tensor and the deviatoric part  of this tensor .

The parameter  in Equation represents the ratio between the yield stresses in compression and tension. These two stress data provide sufficient information to define the shape of the yield surface. By setting  we get the von Mises yield surface as a special case of the Raghava function. Further, the isotropic strain hardening or softening  of Part A is a function of the accumulated plastic strain , and it is controlled by the saturation stress  and the hardening or softening parameter , viz.



A non-associated viscoplastic flow rule is assumed to define the plastic velocity gradient on the intermediate configuration as



where the plastic potential  is defined in the form



Here,  is the plastic dilation parameter, determining the increase of volume during plastic flow.

The equivalent plastic strain rate  of Equation is defined by the constitutive relation



In this expression, two rate-sensitivity parameters,  and , are introduced.

Part B of the material model describes a hyperelastic entropic resistance originally proposed by Arruda and Boyce ([1993](#_ENREF_1" \o "Arruda, 1993 #114))



where  is the initial elastic modulus of Part B,  is the locking stretch, and  is the inverse function of the Langevin function which is defined as . The Jacobian  is . The average total stretch ratio  is calculated as



where  is the distortional left Cauchy-Green deformation tensor, and  denotes the distortional part of .

The model involves 11 coefficients to be determined from uniaxial tension and compression tests. Neither thermal effects nor a fracture criterion is incorporated in the model. For further details about the model it is referred to Polanco-Loria et al. ([2010](#_ENREF_20)).

## Material parameters

The material model has been designed in a such way that its parameters can be determined from simple uniaxial tension and compression tests, as described by [Ognedal et al. (2012)](#_ENREF_19). The parameters for this particular PVC and HDPE have earlier been determined by [Hovden (2010)](#_ENREF_12) and are listed in Table 2. It is important to note that the notched specimen tests were not used in the determination of the material parameters.

The Raghava functions defined by the pressure sensitivity parameter, , and the plastic dilation parameter, , are plotted in Figure 16. The figure shows the Raghava equivalent stress  and the flow potential  of PVC and HDPE as functions of the stress invariants  and  in a stress space normalized with respect to . It is clearly seen that PVC requires a higher stress to reach the yield limit in compression than in tension. This is not the case for HDPE. Also in the plastic potential there is a clear difference between the two materials. During plastic deformation, this leads to different responses of PVC and HDPE because the gradients of the potential functions do not have the same directions in stress space.

# Results from numerical simulations

With the purpose of comparing the results from the numerical simulations to the results from the experimental tests, some of the same geometrical measures were extracted. These measures were the length  spanning over the root of the notch, the minimum cross section radius , and the global displacement and force. Like in the experimental tests, the initial values of  and  are = 2 mm and = 3 mm. Moreover, the average stresses and strains were computed in a similar manner as for the experimental tests, see Equation to Equation .

Force-displacement relationships from the numerical simulations of the PVC specimens are plotted with dotted lines in Figure 7. The response of the smooth PVC specimen and the specimen with = 20 mm is rather well captured by the finite element model. Moreover, it is seen that the maximum force level in PVC is somewhat overestimated for the specimens with smaller notch radius. The PVC specimens from the laboratory tests all reach about the same maximum force level. The numerical simulations, however, predict a slightly higher maximum force for the specimens with smaller notch radius. The dotted lines in Figure 8 represent the response from the numerical simulations of the HDPE specimens. It is seen that the numerical model generally overestimates the maximum force, but it captures that the specimen with smallest notch radius experiences the highest maximum force while the smooth specimen reaches the lowest.

The average axial stress and strain were computed respectively from Equation (1) and Equation . The results are plotted in sub-figures b) in Figure 9 and Figure 10 for the PVC and the HDPE in turn. As for the force-displacement relationships, also the stress-strain curves for PVC specimens with small notch radii are overestimated by the finite element model. During the first part of the deformation of the HDPE, the general trend is that the results from the numerical simulations are rather good. However, the numerical models predict monotonic strain-hardening for all samples, while the experiments, due to damage, show strain-softening in the two HDPE specimens with highest stress triaxiality.

The rates of average axial strain  at the state of maximum force in the numerical simulation of each test are presented in Table 3. These values are similar to those found in the experimental tests, listed in Table 1.

Comparison of the contraction of the minimum cross section of the finite element models and the experimental tests, see Figure 12 and Figure 13, shows how the radial strain and hence volume change is reproduced by the simulations. For the specimens with lowest stress triaxialities, the results are rather good. However, the finite element model predicts stronger contraction of the minimum cross section than what is observed in the experiments for the specimens with smaller notch radii and thus higher stress triaxialities. The volume increase is therefore likely to be underestimated in the numerical simulations

# Discussion

## Experimental tests

Axisymmetric tensile bars with and without notch are tested in uniaxial tension. Different notch radii are employed to investigate the mechanical response at different stress triaxialities. As seen from Figure 6, the stress triaxiality ratio increases when the notch radius  is reduced.

All the tested specimens have force-displacement relationships where the peak force is followed by a reduction of the force level, see Figure 7 and Figure 8. An average axial stress is defined as the applied force divided by the current minimum cross section area, see Equation . Thus, the reduction of the minimum cross section due to necking is accounted for in the average axial stress-strain curves plotted in Figure 9 and Figure 10. Yet, a local maximum followed by a drop can also be observed in the stress-strain curves for all PVC specimens and for HDPE-2 and HDPE-08. All these specimens fractured during testing. The presence of such stress peaks may be related to internal damage: If void growth sets in at peak stress, the effective load-bearing cross section is reduced subsequently. The reduction of the effective cross-section area from an increasing void volume fraction cannot be measured by the test setup employed here. By interrupting the deformation and splitting the specimens, as done by Ognedal et al. ([2014](#_ENREF_18" \o "Ognedal, 2014 #220)) for flat tensile specimens and by [Boisot et al. (2011)](#_ENREF_2" \o "Boisot, 2011 #153) for axisymmetric tensile specimens with notch, estimates of the void volume fraction could have been found by using SEM. X-ray tomography is an alternative method that also could have been applied ([Cayzac et al., 2013](#_ENREF_6" \o "Cayzac, 2013 #226)).

The average axial stress at peak force is interpreted as the yield stress in the following. These values are plotted against the initial notch diameter in Figure 17, where triangles represent results from experimental tests. The figure shows how the initial notch radius , and therefore the stress triaxiality, influences the axial component of the stress tensor at yielding of the two materials. In materials with pressure independent yielding, the axial component of the stress tensor at yielding increases with increasing stress triaxiality. This is the general trend for HDPE; smaller  leads to a somewhat higher average axial stress at maximum force, , as for pressure insensitive materials. This is in agreement with previous results from uniaxial tension and compression tests ([Moura et al., 2010](#_ENREF_16)) resulting in a pressure sensitivity parameter of = 1 in the constitutive model, see Table 2. On the contrary, in a pressure sensitive material, e.g. the PVC, also the hydrostatic stress component contributes to reaching the onset of plastic flow. Yielding at higher stress triaxialities can therefore occur without any increase of the average axial stress at maximum force, as observed for the PVC.

Table 1 reveals that the rate of average axial strain is higher for the PVC specimens with small notch radius than for those with larger notch radius. Since the PVC is sensitive to strain rate, this may contribute to a minor lift of the left part of the dotted curve connecting the triangle markers in Figure 17. Despite this, the shape of the curve is relatively flat, again indicating damage.

The change of volume in the notched region can be presented in terms of volume strain, as in Figure 11, or in terms of radial strain ([Boisot et al., 2011](#_ENREF_2); [Castagnet and Deburck, 2007](#_ENREF_5)), see Figure 12 and Figure 13. One major difference between the two measures applied in this study is that the volume strain is calculated for a rather large zone between the two central markers in Figure 4, while the radial strain is measured in the minimum cross section where the strain is most localized. However, the same trend is found by the two ways of presenting volume change: the dilation increases with decreasing . This is also the case for the HDPE, despite its isochoric flow for smooth specimens in uniaxial tension. It is reasonable to relate the volume change, both in PVC and HDPE, to void growth. Voids in the PVC specimens were observed in terms of stress whitening. No stress whitening was observed for the HDPE. Still, traces of voids in both materials are found from examining the fracture surfaces as demonstrated in Figure 14 and Figure 15.

It is assumed that the presence of particles affects the fracture of the PVC and the HDPE. In addition to HDPE-2 and HDPE-08, all PVC specimens fractured during testing. The fracture surfaces, depicted in Figure 14 and Figure 15, suggest that the fracture was induced by void growth. These voids may originate from debonding of the particles seen in Figure 1. The energy absorbed in particle debonding is pointed out as one potential source of toughening of polymer materials ([Cotterell et al., 2007](#_ENREF_8)). Changes in the matrix material, due to the presence of second-phase particles, is another ([Cotterell et al., 2007](#_ENREF_8); [van Dommelen et al., 2003](#_ENREF_23)). Also the triaxiality of the stress state affects fracture. Laiarinandrasana et al. ([2009](#_ENREF_13" \o "Laiarinandrasana, 2009 #154)) discussed the effect of strain rate, temperature and stress triaxiality on the fracture of a polyvinylidene fluoride with significant porosity. They report more ductile fracture behaviour for axisymmetric tensile specimens with larger notch radii, i.e. lower triaxialities, than for smaller ones, while higher strain rate and high stress triaxialities gave more brittle fracture. This is in accordance with the experience from the present study. The HDPE specimens with large  were too ductile to fracture, while the specimens with lower  fractured.

The fracture surfaces of the PVC specimens have a rather rough topography. An impression from comparing the different PVC specimens is that a larger  caused a rougher fracture surface. The fracture surfaces of the two HDPE specimens are more planar, oriented transverse to the loading direction. Larger, but fewer, traces of voids can be seen on the fracture surface of the HDPE-2 specimen than on the HDPE-08 specimen. Moreover, the average axial strain at fracture was higher for HDPE-2 than for HDPE-08, see Figure 10 a). This indicates that voids may coalesce during the deformation process.

The radial distribution of stress triaxiality found from the numerical simulation of elastic deformation of specimens with = 0.8 mm, see Figure 6, reveals that the stress triaxiality is not at its maximum in the centre of the specimen, but at a location closer to the surface. The increased void size at positions approaching the boundary of the fracture surface of HDPE-08, see Figure 15 b), indicates that void growth has been more pronounced in this zone. For a similar test specimen, also with a low value of , Laiarinandrasana et al. ([2012](#_ENREF_14" \o "Laiarinandrasana, 2012 #166)) identified the same zone as the location of maximum damage. This was done for polyamide 6 both by finite element modelling and by experimental tests employing X-ray tomography. If the minimum diameter  is considerably larger than , the stress triaxiality does not increase monotonically towards the specimen centre.

It should be emphasized that several of the entities presented in Section 4 are averaged over a length, an area or a volume. Except for the cross section radius , the deformations are not measured locally. Local values of axial strain in the minimum cross section are certainly higher than the average axial strain . It is likely that also the local strain rate in the minimum cross section is higher than what we have measured. Also the temperature might have been higher in the notched specimens as an effect of increased strain rate.

## Comparison of numerical simulations and experimental tests

The results from the laboratory tests were compared with the results from numerical simulations employing the hyperelastic-viscoplastic material model proposed by Polanco-Loria et al. ([2010](#_ENREF_20)). The purpose was to identify to which extent this phenomenological material model, with material parameters determined from uniaxial tension and compression tests, captured the mechanical behaviour at higher stress triaxialities.

Figure 7 and Figure 8 display force-displacement relationships from experiments and numerical simulations. The numerical model predicts the behaviour of the PVC rather well at moderate stress triaxialities. For higher stress triaxialities, the maximum force is slightly over-estimated. The behaviour of the HDPE from the experimental tests is generally well reproduced by the numerical simulations. However, the softening observed for HDPE-2 and HDPE-08 due to damage is not included in the numerical model.

In Figure 9 a) it is seen that all the notched PVC specimens from the laboratory tests exhibit more or less the same peak axial stress. The numerical simulations displayed in sub-figure b), however, predict that the peak stress increases with the stress triaxiality. Turning the attention to the axial stress-strain relationship of the HDPE displayed in Figure 10, it is seen that the yield stress increases with stress triaxiality, both in the experimental tests, see sub-figure a), and in the numerical simulations in sub-figure b). The two tests HDPE-2 and HDPE-08 exhibit strain-softening after onset of yielding in the experimental tests. The numerical simulations, on the other hand, predict strain-hardening. Better results could probably have been obtained by introducing damage in the material model. However, this would have been at the cost of increasing the number of parameters.

In the experiments, the smooth HDPE specimen experienced severe strain localization, maybe due to an uneven lathe surface finish. This strain localization is not captured in the numerical model. Therefore, the local strains in the numerical model ceases at a lower level than in the experiment, even though they had the same global displacement.

The crosses in Figure 17 visualize how the stress triaxiality influences the yield stress in the numerical simulations of the PVC and the HDPE. As already discussed, all experimental test specimens of PVC reach about the same peak stress independent of the notch size, whereas the numerical simulations predict an increase in peak stress with stress triaxiality. This means that the yield stress in the real PVC material has a higher pressure-sensitivity than what is represented by the constitutive model. The behaviour of the HDPE is somewhat better captured in the simulations. It seems that a pressure sensitivity parameter of = 1.3 for PVC does not reduce the yield stress in the numerical model sufficiently for high stress triaxialities. For HDPE, the choice of = 1 seems to fit better.

High stress triaxiality introduces damage in terms of void growth in the experimental tests of both materials. For the PVC the damage might affect the value of obtained maximum force, while for HDPE it becomes important after the maximum force level is reached. Evolution of damage is not included in the constitutive model.

Both for the PVC and the HDPE the values of  predicted by the numerical simulations are too high compared to the experimental tests, see Figure 17. To check whether this difference might be related to strain rate, the average axial strain rate  at the point of maximum force was extracted from the numerical simulation of each test. The values presented in Table 3 are similar to those found in the experimental tests, see Table 1. Therefore, the mismatch in the maximum force level can probably not be ascribed to differences in strain rate.

The experimental tests show that the plastic dilation increases with the stress triaxiality in both materials. This is not well captured in the numerical simulations, as seen from the contraction of the minimum cross section plotted in terms of radial strain in Figure 12 and Figure 13.

## Suggestions for improvements

An approach to measure the local strains, instead of average strains, could be to use digital image correlation. In fact, some introductory tests on axisymmetric notched tensile bars were carried out using 3D-DIC employing two CCD cameras. The small size of the notch combined with the large local deformations and the double-curved surface caused difficulties with the image quality and also so much noise that the strain measurements were poor. Therefore, the simple test setup described here, involving one camera focusing on the rim of the test specimen so that its curvature could be traced, was chosen.

[Ognedal et al. (2014)](#_ENREF_18) suggest that the peak stress in the mineral-filled PVC can be interpreted as a “matrix-particle debonding stress” rather than a “yield stress of the PVC matrix”. Micrographs of HDPE reveal that also this material contains some amount of particles, see Figure 1 b), although the amount is much less than for the PVC. In this perspective, it is possible to imagine that a highly triaxial stress state stimulates the process of particle debonding. Moreover, such a stress state most probably enhances the void growth around the debonded particles. Therefore, the numerical results might have been improved by using a yield criterion and a plastic potential with blunter shape in the domain of hydrostatic tension. Then the yield stress would have been lower for higher stress triaxialities. Also, the gradient of the plastic potential would produce higher volume strains.

For the modelling of the mineral-filled PVC material, a softening function was employed by using that , see Equation and Table 2. This softening can be interpreted as the reduction of strength in the material due to damage. It might have been an interesting modification of the material model to control, or just scale, the softening by the volumetric strain instead of the equivalent plastic strain. This would not affect the prediction of the yield stress, i.e. the debonding stress, only the subsequent behaviour.

Another approach of modelling the behaviour of these materials subjected to high stress triaxiality could have been to use a material model based on the mechanisms of void growth. Boisot et al. ([2011](#_ENREF_2" \o "Boisot, 2011 #153)) report good numerical results from employing a modified Gurson-Needleman-Tvergaard model on axisymmetric notched specimens of polyamide 11 with an initial porosity of 1%. Especially when it comes to peak stress, stress softening and the stress plateau, they state that their results are in good agreement with experimental data. However, such a material model requires a more complicated calibration process including determination of the initial porosity.

# Conclusion

The experimental part of this paper presents laboratory tests designed to investigate how the mechanical behaviour of two different polymers is influenced by hydrostatic stress. It was found that the yield stress of the mineral-filled PVC is sensitive to hydrostatic stress. Also the plastic dilation of the material changes with hydrostatic stress: higher stress triaxiality lead to higher dilation. Turning attention to the HDPE, the yield stress shows hardly any sensitivity to pressure. However, the change of volume at higher stress triaxialities is evident: higher stress triaxialities leads to more volume increase in the HPDE. Damage, in the terms of void growth, is identified as the source of the plastic dilation in both materials. Also the fracture of both materials seems to be related to voids.

The aim of the numerical part of the study was to investigate whether a phenomenological material model, with parameters determined from uniaxial tension and compression tests, could predict the mechanical behaviour at high stress triaxialities. The force-displacement behaviour of the notched axisymmetric tensile bars was reproduced with reasonable accuracy for both materials. However, the experimentally observed volume change at high stress triaxialities was poorly predicted. Dilation due to void growth was observed to increase with stress triaxiality in the experimental tests. This was not well captured by the numerical simulations. Numerical results might have been improved by introducing damage in the constitutive relations at the cost of increasing the number of model parameters.

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Figures and captions

|  |  |
| --- | --- |
| a) | b) |

Figure 1 *SEM micrographs of the initial microstructure of a) PVC and b) HDPE.*

|  |
| --- |
| a) |
| b) |

Figure 2 *Specimen geometry of a) notched axisymmetric tensile bar and b) smooth axisymmetric tensile bar (*[*Børvik et al., 2001*](#_ENREF_4)*). Measures are given in mm.*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  |  |  |  |
| a) | b) | c) | d) | e) |

Figure 3 *The geometries of a) the smooth test specimen, and test specimens with initial notch radii  equal to b) 20 mm, c) 5 mm, d) 2 mm and e) 0.8 mm.*

|  |  |
| --- | --- |
| a) | b) |

**Figure 4***A test specimen with notch radius =5 mm a) before deformation and b) during deformation. The black dots were applied to the specimen before the test to serve as an optical extensometer.*

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| --- |
|  |

**Figure5** *Example of mesh refinement in the notch of an axisymmetric bar with = 5 mm. The height of the part with the finest mesh is = 2 mm.*

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|  |

**Figure 6***Variation of the stress triaxiality ratio, , in the minimum cross section of the test specimens from the FE simulations of elastic deformation. Solid lines are applied for PVC and dashed lines for HDPE.*

|  |  |
| --- | --- |
| a) | b) |
| c) | d) |
| e) |  |

Figure 7 *Force plotted against cross-head displacement for a) PVC-smooth, b) PVC-20, c) PVC-5, d) PVC-2 and e) PVC-08.*

|  |  |
| --- | --- |
| a) | b) |
| c) | d) |
| e) |  |

Figure 8 *Force plotted against cross-head displacement for a) HDPE-smooth, b) HDPE-20, c) HDPE-5, d) HDPE-2 and e) HDPE-08.*

|  |  |
| --- | --- |
| a) | b) |

Figure 9 *Average axial stress plotted against average axial strain for PVC specimens from a) representative experimental tests and b) numerical simulations.*

|  |  |
| --- | --- |
| a) | b) |

Figure 10 *Average axial stress plotted against average axial strain for HDPE specimens from a) representative experimental tests and b) numerical simulations.*

|  |  |
| --- | --- |
| a) | b) |

Figure 11 *Volume strain plotted against average axial strain from representative experimental tests of notched specimens of a) PVC and b) HDPE.*

|  |  |
| --- | --- |
|  |  |

Figure 12 *Average radial strain plotted against average axial strain for notched PVC specimens from a) representative experimental tests and b) numerical simulations.*

|  |  |
| --- | --- |
| a) | b) |

Figure 13 *Average radial strain plotted against average axial strain for notched HDPE specimens from a) representative experimental tests and b) numerical simulations.*

|  |  |
| --- | --- |
| a) | b) |
| c) | d) |

Figure 14 *Fracture surface of representative test specimen a) PVC-20, b) PVC-5, c) PVC-2 and d) PVC-08.*

|  |  |
| --- | --- |
| a) | b) |

Figure 15 *Fracture surface of representative test specimen a) HDPE-2 and b) HDPE-08.*

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Figure 16 *Raghava equivalent stress  (solid lines) and potential function* *(dotted lines) for PVC and HDPE in a dimensionless stress space defined by the stress invariants  and  using the tensile yield stress*  *for normalization. The dashed lines represent the stress states of uniaxial tension and compression, namely*  *and* *.*

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| --- |
|  |

**Figure 17** *The stress level at maximum force plotted against initial notch radius* *.*

Tables

Table 1 *Rate of average axial strain, * [], *at maximum force in the representative tests on PVC and HDPE specimens.*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| [] | Smooth | 20 mm | 5 mm | 2 mm | 0.8 mm |
| PVC | 0.0015 | 0.012 | 0.018 | 0.018 | 0.021 |
| HDPE | 0.0024 | 0.0059 | 0.0070 | 0.012 | 0.013 |

Table 2 *Material parameters for 10 mm thick extruded plates of PVC and HDPE. The parameters are determined by Hovden (*[*2010*](#_ENREF_12)*).*

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | [MPa] |  | [s-1] |  | [MPa] | [MPa] |  |  |  | [MPa] |  |
| PVC | 3000 | 0.3 | 0.0010 | 0.070 | 46.8 | 5.50 | 1.92 | 1.3 | 1.27 | 37.8 | 15.0 |
| HDPE | 800 | 0.4 | 0.0007 | 0.108 | 13.0 | 1.74 | 7.75 | 1.0 | 1.04 | 23.9 | 39.6 |

Table 3 *Rate of average axial strain, * [], *at maximum force in simulations of PVC and HDPE specimens.*

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| [] | Smooth | 20 mm | 5 mm | | 2 mm | | 0.8 mm | |
| PVC | 0.00096 | 0.0087 | | 0.015 | | 0.019 | | 0.017 |
| HDPE | 0.00910 | 0.0068 | | 0.010 | | 0.012 | | 0.011 |