

TEMPERATURE PARAMETER EFFECT ON THE FRACTURE BEHAVIOUR OF THE POLYMER MATERIAL: CASE OF HDPE

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Abstract

In this study, the finite element method is used to analyze the effect of a geometric discontinuity on the fracture behaviour of polymer material (High-Density-Polyethylene; HDPE). The effect of the temperature parameter on the distribution of stresses and strains at the notch (geometric discontinuity) has been studied. The results obtained numerically show a good correlation with experimental results. The Rice-Tracey (RT) model is used to reproduce the macroscopic mechanical behavior of the HDPE material in terms of stress versus strain for different temperature level.

Key words: High-Density-Polyethylene; HDPE, Finite Element Method FEM, Rice-Tracey (RT) model, Temperature, Behaviour Law of Polymer

1. INTRODUCTION

The prediction of service life of polymer materials has been the subject of numerous studies (Andena et al. 2009, Frank et al. 2009, Hoang et al. 2008, Khelif et al. 2007 and Krishnaswamy et al. 2005). A typical requirement for pipes used for the distribution of gas or water is estimated with a life at least 50 years. The traditional method to evaluate the lifetime of pressure pipes plastic material is based on the hydrostatic pressure testing (EN ISO 9080). Plastic pipes have been used successfully today, especially pipes polyethylene (PE), HDPE is widely used in pipelines of gas and water (Lang et al. 1997, Janson 1999). In 2007, the worldwide demand for pipes made of poly-ethylene with high density (HDPE) was about 3.7 million tons and a growth rate of 6% per year up to 4.9 million tons is expected in 2012 according to Brescia (Brescia 2008). The polymer pipes offer several advantages in comparison to metallic pipes: they have good resistance to wear and corrosion, low density, low cost, easy of installation, production of complex shape (elbow of connection in pipelines). But the mechanical properties by polymers materials are very sensitive to some parameters such as strain rate and temperature. It is well known that the ductile material (HDPE) is controlled by three steps, namely the nucleation of micro-voids, the mechanisms of growth and finally the coalescence of micro-voids. To describe this process of damage and failure of structure, several models based on local approaches have been proposed in the literature such as the Rice-Tracey model (Rice et al. 1969). Finite element analysis (FEA) is an important tool to design a practical mechanical component, such as the pipelines of polymer. In this paper, the Finite Element Method (FEM) based on the application of Rice-Tracey model to describe the evolution of damage in the structure. The sensitivity of temperature parameter on the fracture behavior of HDPE materials is also examined.

2. GEOMETRICAL, MATERIALS MODELS AND FINITE ELEMENT MODELLING

The specimen geometry used is shown in Figure 1. These specimens are called axisymmetric notched specimen (AE). With the explosive growth of computer technology, the use of a software finite element analysis to modeling the fracture behavior of structures in any sector is a great interest, especially in the case of structures on polymer containing a defect. The fracture behavior of structure is analyzed by the analysis of field stress and strain at the near in the geometric discontinuity. For this, we used the finite element code CASTEM developed by the Department of Mechanics and Technology CEA Saclay (Cast3M 2008). An elastic-plastic behavior was undertaken for all cases studied (Hobeika et al. 2000). We modeled four axisymmetric notched specimens namely: AE2, AE4, AE6, AE8 in order to determine the local parameters (the field of stress and strain at the near in the geometric discontinuity). The theory of incremental plasticity is introduced to model the material nonlinearity. The iterative method of Newton-Raphson is used as an approach to solve nonlinear equations by finite elements.

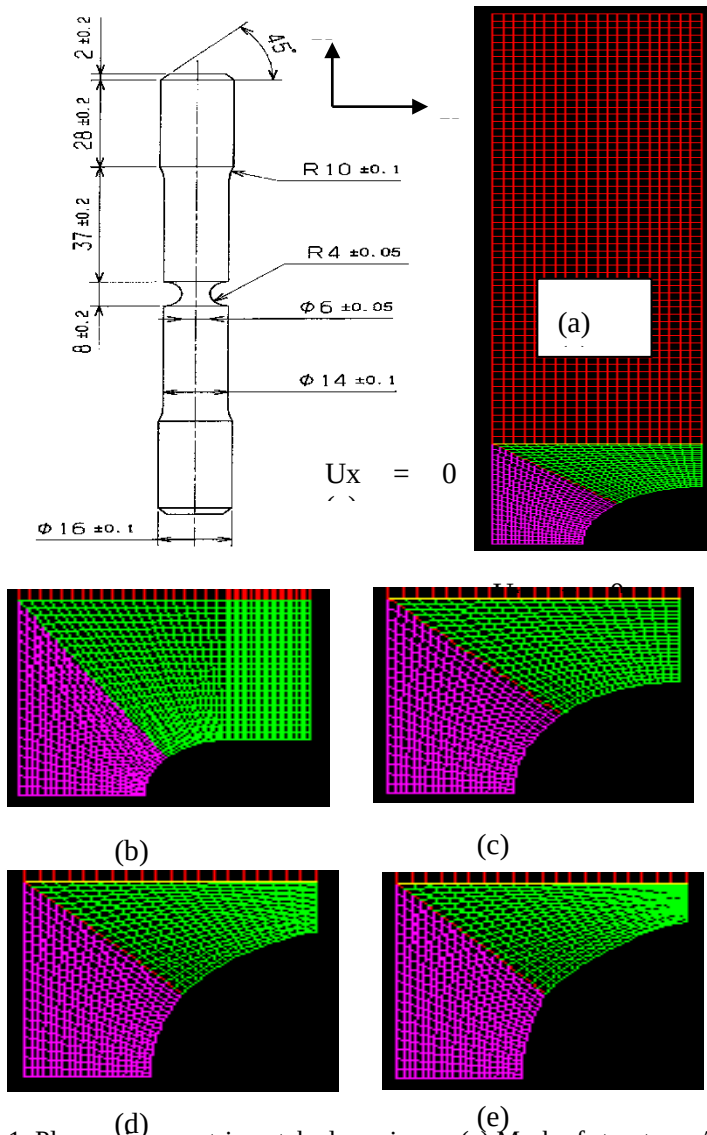


Figure 1. Plans axisymmetric notched specimens (a) Mesh of structure, AE and the Meshes of axisymmetric notched specimens (b) AE2, (c) AE4, (d) AE6, (e) AE8

We considered the symmetry of the specimen relative to the plane of minimum cross section at the bottom of the notch and symmetry relative to the axis of revolution. Therefore only one quarter of the specimen is modelled by two dimensional axisymmetric in order to reduce the calculation time. The mesh size of each specimen (AE) is composed of several set areas. We proceeded in the same way for modelling the mesh for each specimen. The singularity at the near of the geometric discontinuity is modelled by special elements in order to increase the precision of calculation. The typical Mesh for the four specimens AE2, AE4, AE6 and AE10 are shown in Figure I (b) (c) (d) (e).

3. RESULTS AND DISCUSSIONS

3.1. Stress distribution at the radius of curvature

Figure 2 shows the isovalues of the stress (σ_{yy}) along the loading direction, the equivalent stress (Von Mises stress: σ_{equi}) and strain (ϵ_{yy}) in the direction of loading, respectively.

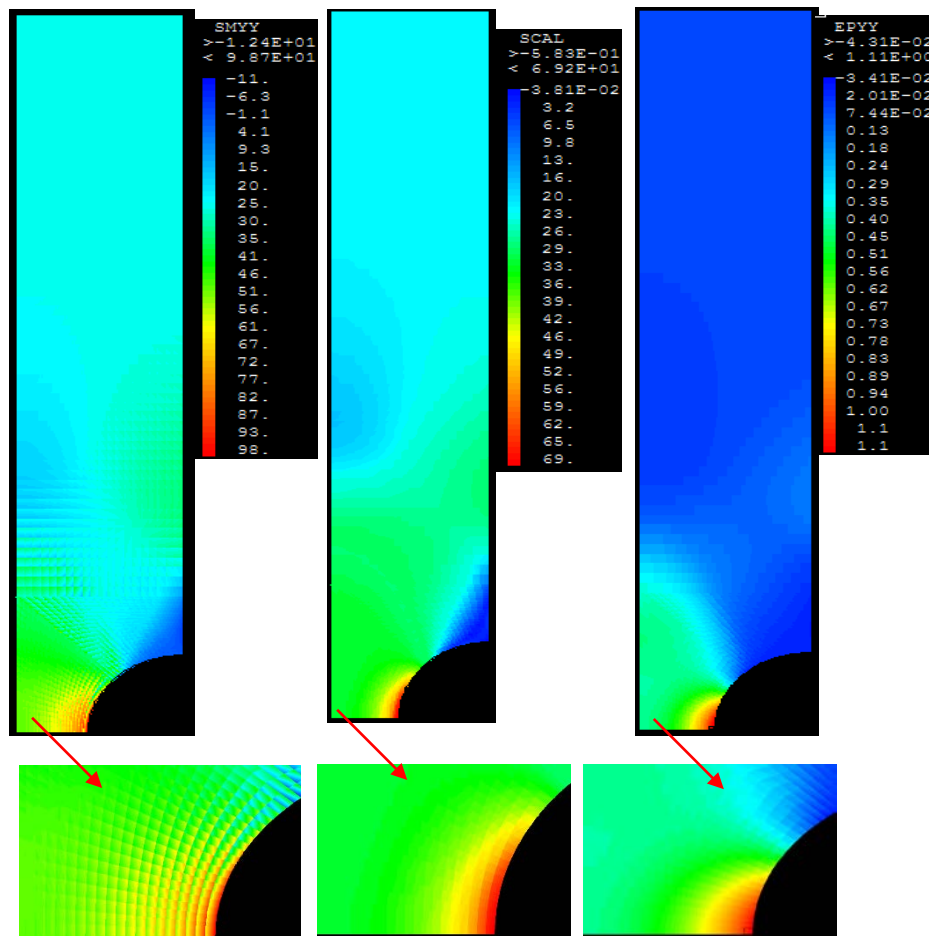


Figure 2. Representation of stress and strain for AE2: (a) σ_{yy} , (b) σ_{eq} and (c) ϵ_{yy}

We note that the stress field is important at the near in the geometric discontinuity and weakens when far from the geometrical defect (geometric discontinuity). A first observation of the reading of this figure (Figure. 2) is that the highest values of these constraints ($\sigma_{yy} = 181$ MPa and $\sigma_{eq} = 108$ MPa) and the strain ($\epsilon_{yy} = 1.5$) will be located near the notch (geometric discontinuity), their distributions are not uniform in this position. This is obviously due to the effect of the geometrical parameters of the specimen and the loading condition. Therefore the presence of this high stress gradient, at this location which can lead to the crack initiation and propagation under loading in the service. Several studies (Anderson et al. 2014, Abushawashi et al. 2013, Bridgman 1964) showed that the radius of curvature is a very important factor in the mechanical behaviour of poly-ethylene, especially at high temperature. In this paragraph the effect of radius of curvature on the distribution of stress and strain in geometric discontinuity is analysed. The damage is evaluated by the analysis of stress and strain at the geometric discontinuity for four configurations: AE2, AE4, AE6 and AE8. For this, we chose the same specimen previously treated (Figure. 2) with different radius of curvature.

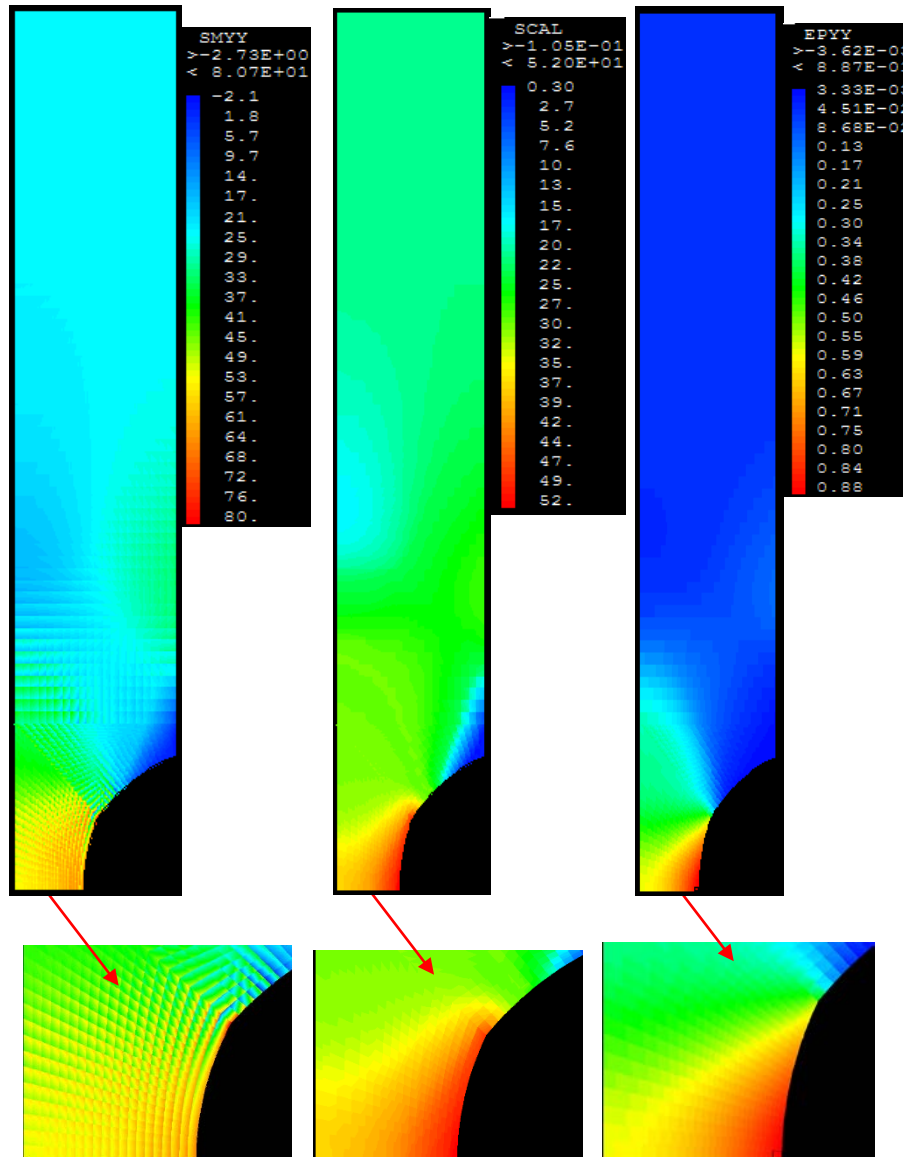


Figure 3. Representation of stress and strain for AE8: (a) σ_{yy} , (b) σ_{eq} and (c) ε_{yy}

Figure 3 show the stress distribution (σ_{yy}) along the direction of loading, the equivalent stress (Von Mises stress: σ_{eq}) and deformation (ε_{yy}) in the direction of loading for the AE8 configuration. A similar trend was observed for all configurations analysed; AE2, AE4, AE6 and AE8. In other words, a small notch radius leads to high field of stress and strain close to the geometrical discontinuity

By comparing, the values of the equivalent stress (AE2) in Figure 2 and equivalent stress (AE8) in Figure 3, it can be noted that the radius of curvature lower is more dangerous than the radius of curvature higher. The value of σ_{eq} for the AE2 configuration is almost twice more important than that of AE8 configuration. This behaviour is probably related to the non-homogeneous distribution of the local stress field near to the geometrical defect due to the change of geometry of the geometrical discontinuity under loading. It may be noted that the low radius of curvature accelerate the risk of crack initiation and hence rapid failure of structure in service. It can be conclude that the geometrical discontinuity has a very important effect on the fracture behavior of polymer materials.

Figure 4-a show the evolution of the rate of triaxiality versus the equivalent plastic strain. These values were calculated in the center of the mesh in the center of the specimen. One can notice that the small notch radius (AE2) has a plastic strain important and a very high rate of triaxiality which leading a rapid failure of structure.

The increase in notch radius leads to a significant reduction of the rate of triaxiality and therefore a low risk of rupture compared to the case of small notch radius. This result has been confirmed previously in the analysis of the stress and strain field close to the geometric discontinuity.

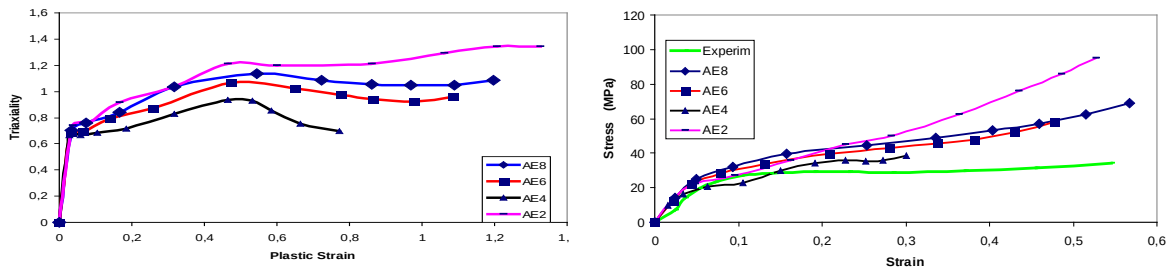


Figure 4. Evolution of (a) Triaxiality versus equivalent plastic strain, (b) true stress versus true strain; comparison experimental with numerical result at $T = 23^{\circ}\text{C}$

Figure 4-b shows the evolution of the true stress versus of the true strain for four configuration analysed (AE2, AE4, AE6, AE8) obtained by numerical simulation at room temperature ($T = 23^{\circ}\text{C}$). For larger notch radius (AE8), we can observe a good correlation between the numerical and experimental result, except for large deformations where the difference appears more important between the simulated and experimental curves.

3. 2. Temperature effect on the behavior of HDPE

A comparison of the results obtained numerically with those obtained experimentally on axisymmetric notched specimens (AE2, AE4, AE6 and AE8) for different values of temperature is given later in this paper. This analysis has contributed to a better understanding of the effect of temperature on the fracture behaviour of HDPE.

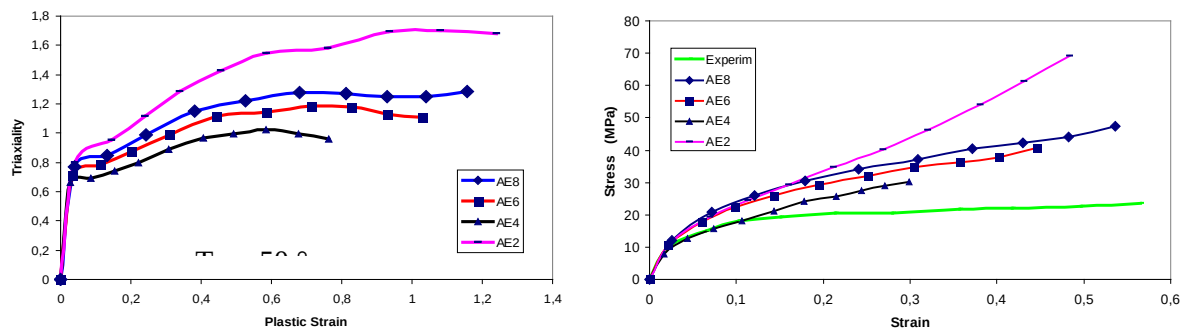


Figure 5. Evolution of (a) Triaxiality versus equivalent plastic strain, (b) true stress versus true strain; comparison experimental with numerical result at $T = 50^{\circ}\text{C}$

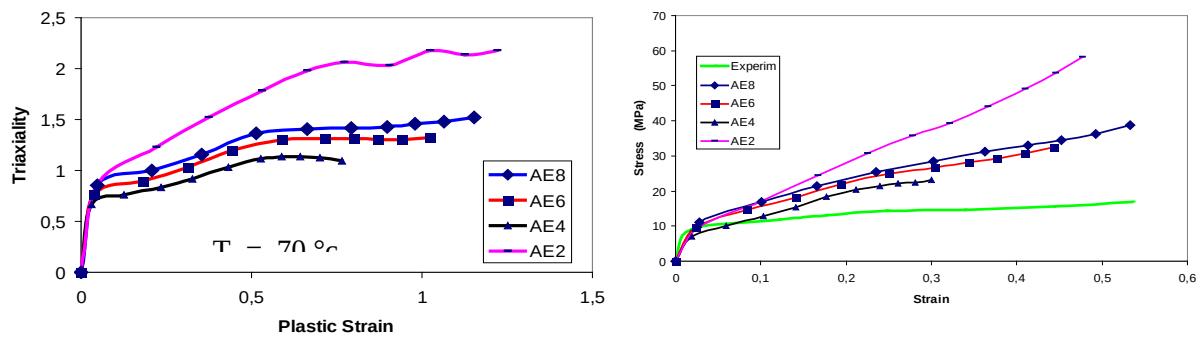


Figure 6. Evolution of (a) Triaxiality versus equivalent plastic strain, (b) true stress versus true strain; comparison experimental with numerical result at $T = 70^{\circ}\text{C}$

Figures 5 and 6 shows the evolution the rate of the stress triaxiality at the center of samples (AE) as a function of the equivalent plastic strain and the evolution of the true stress as a function of the true strain for the four configuration analyzed previously (AE2, AE4, AE6, AE8: comparison of numerical and experimental results) for two level of temperatures ($T = 50^{\circ}\text{C}$ and $T = 70^{\circ}\text{C}$). A first observation of reading from these figures (Figure 5-6) is that the low radius curvatures are dangerous compared to high low radius curvature whatever the level of temperature for axisymmetric notched specimen AE. This is obviously due to the effect of the notch geometry of AE2 specimen which generates a stress concentration and a large plastic strain at the center of the specimen for this loading condition. We also note that, regardless of the geometric configuration (AE2, AE4, AE6, AE8), an increase of the temperature parameter leads to a decrease in the stress and strain fields in the geometric discontinuity. The main reason for this variable behaviour is due to change of temperature service; which leads of change of material behavior law and consequently a degradation of mechanical properties for the poly-ethylene at high temperature especially for low radius curvature AE2. Guermazi (Guermazi et al. 2009) demonstrated from an experimental analysis that, there is a degradation of mechanical properties by the aging of pipeline coating under several temperatures ($T = 23, 70$ and 90°C). In conclusion, we can say that the results presented show that the model of Rice-Tracey (RT) is used to reproduce the macroscopic mechanical behavior of HDPE material. According to the experimental and numerical analysis, it can be seen that the result gave a good correlation between various methods, thus establishing confidence in the results of the finite element modelling to study the fracture behaviour of HDPE material

4. CONCLUSION

This study was carried out to analyze the effect of a geometric discontinuity (notch) on the fracture behaviour of an axisymmetric specimen of polyethylene (HDPE) based on the Rice-Tracey model for various level of temperature. From these results, we can deduce the following conclusions:

- A good correlation between experimental and numerical results whatever the geometrical configuration of AE.
- These results clearly show that the stresses are concentrated at the geometric discontinuity and decrease with the increasing of the triaxiality parameter.
- The elevations of temperature decrease the mechanical behaviour of polymer materials (HDPE).
- The model of Rice-Tracey (RT) can be used to reproduce the macroscopic mechanical behaviour of HDPE material.

REFERENCES

- Abushawashi Y, Xiao X, Astakhov V, 2013, 'A novel approach for determining material constitutive parameters for a wide range of triaxiality under plane strain loading conditions', *International Journal of Mechanical Sciences*, vol. 74, pp. 133–42.
- Anderson D, Winkler S, Bardelcik A, Worswick MJ, 2014, 'Influence of stress triaxiality and strain rate on the failure behavior of a dual-phase DP780 steel', *Materials and Design*, vol.60, pp. 198–07.
- Andena L, Rink M, Frassine R, Corrieri R, 2009, 'A fracture mechanics approach for the prediction of the failure time of polybutene pipes', *Engng Fract Mech*, vol. 76(18), pp. 2666–77.
- Brescia G, 2008, 'The changing world of the chemical industry and its impact on the pipe industry', *In: Conference of plastics pipes XIV*, Budapest, Hungary.
- Bridgman PW, 1964, 'Studies in large plastic flow and fracture', *Harvard University Press*, Cambridge, Massachusetts.
- Castem (www-cast3m.cea.fr)
- EN ISO 9080, 2003, 'Plastics piping and ducting systems – determination of the long-term hydrostatic strength of thermoplastics materials in pipe form by extrapolation'.
- Frank A, Pinter G, Lang RW, 2009, 'Prediction of the remaining lifetime of polyethylene pipes after up to 30 years in use', *Polym Test*, vol. 28, pp. 737–45.
- Guermazi N, Elleuch K, Ayedi H, 2009, 'The effect of time and aging temperature on structural and mechanical properties of pipeline coating', *Materials and Design*, vol.30, pp. 2006–10.
- Hoang EM, Lowe D, 2008, 'Lifetime prediction of a blue PE100 water pipe', *Polym Degrad Stab*, vol. 93, pp. 1496–1503.
- Hobeika S., Men Y., Strobl G, 2000, 'Temperature and strain rate independence of critical strains in polyethylene and poly(ethylene-co-vinyl acetate)', *Macromolecules*, vol. 33, pp. 1827-1833.
- Janson LE, 1999, 'Plastics pipes for water supply and sewage disposal', *Borealis*, Stockholm, Sweden.
- Khelif R, Chateaneuf A, Chaoui K, 2007, 'Reliability-based assessment of polyethylene pipe creep lifetime', *Int J Press Vessels Pip*, vol. 84, pp. 697–707.
- Krishnaswamy Rajendra K, 2005, 'Analysis of ductile and brittle failures from creep rupture testing of high-density polyethylene (HDPE) pipes', *Polymer*, vol. 46(26), pp. 11664–72.
- Lang RW, Stern A, Doerner G, 1997, 'Applicability and limitations of current lifetime prediction models for thermoplastics pipes under internal pressure', *Die Ang Mak Chemie*, vol. 247, pp. 131–7.
- Rice JR, Tracey DM, 1969, 'On ductile enlargement of voids in triaxial stress fields', *J Mech Phys Solids*, vol. 17, pp. 201–17.