The effect of residual stresses on crack shape in polymer pipes

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ABSTRACT. *The effect of residual stresses on crack geometry and consequently on crack behaviour in polymer pipes is estimated. Crack geometry has a significant influence on the resulting stress intensity factor value. The shape of a crack in three-dimensional analysis was numerically estimated using a special routine which ensures constant stress intensity factor along the crack front. It was found that the crack shape was influenced by the presence of residual stresses and significant increase of the stress intensity factor for a pipe with residual stresses in comparison with a pipe without residual stresses was observed. An approximative equation for stress intensity factor estimation in a pipe with residual stresses was presented and its accuracy tested.*

INTRODUCTION

A typical requirement for plastic pipes used for gas or water distribution is a lifetime of at least 50 years [1,2]. The traditional method for assessing the lifetime of plastic pressure pipe materials is based on hydrostatic pressure testing [3] (EN ISO 9080).

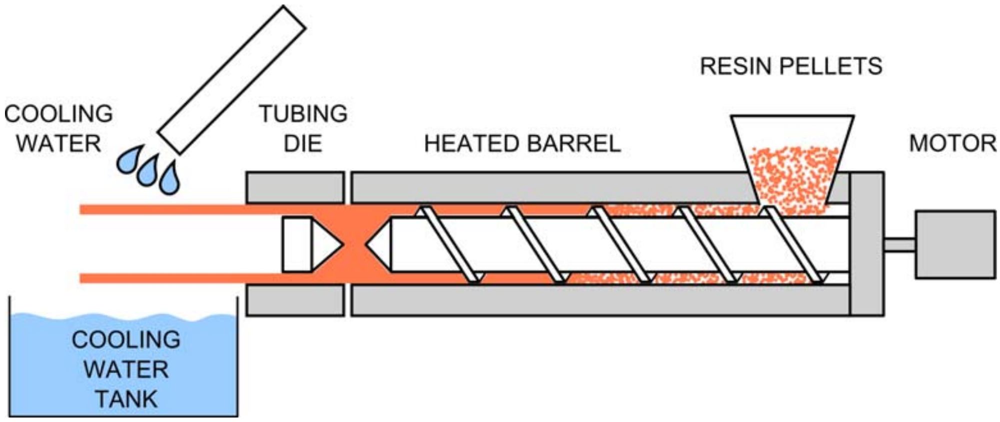

Figure 1. Schema of the extrusion process

Hydrostatic rupture tests are conducted in a specific environment at various pressure levels and at different temperatures. Due to the fact that the failure phenomenon of quasi-brittle crack growth is most relevant for real service, the failure of polymer pipes can be described using fracture mechanics concepts [1,4,5,6]. Usually, the production of the pipes involves the extrusion of molten polymer through an annular die and subsequent rapid cooling of the outside surface of the extruded material, see Fig.1. This technological process introduces the final residual stresses in the pipe, which can be comparable with stresses induced by internal pressure during service [2,7]. Therefore, the effect of residual stresses can be important for lifetime prediction [8,9].

The main aim of the article is to estimate the effect of residual stresses on crack geometry and consequently on crack behaviour. The crack geometry has a significant influence on the resulting stress intensity factor value. The shape of the crack in three-dimensional (3D) analysis is numerically estimated using a special routine, which ensures a constant stress intensity factor along the crack front. The methodology is similar to that used in [6,10]. For a given crack length the crack aspect ratio is iteratively changed to obtain a constant stress intensity factor along the crack front. Based on FEM calculations, the evolution of a creep crack in the case of internal pressure loading taking into account residual stresses, is obtained. The results and methodology presented can be a powerful tool for estimation of a plastic pipe's lifetime.

RESIDUAL STRESSES

Thermal residual stresses in the pipe wall arises from different cooling rates along the inner and outer surface of the pipe [2,7]. A typical (residual) stress distribution along pipe wall thickness is shown in Fig.2b.

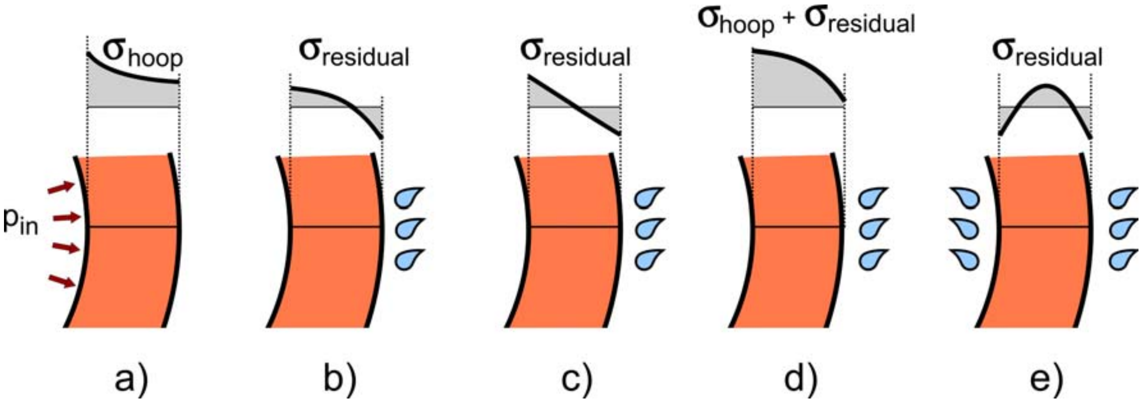

Figure 2. Schema of the tangential stress distribution along pipe wall thickness in the case of a pipe loaded by inner pressure p_{int} only (a); residual stress induced by outer surface cooling process (b); linear approximation of residual stress after outer surface cooling (c); sum of tangential stress from inner pressure and residual stress (d); residual stress induced by both outer and inner surface cooling (e).

Normally, plastic pipes forming in extrusion process are characterised by intensive cooling by water only from the outer pipe wall, the inner wall being in contact with almost stationary air [11]. Under these circumstances the pipe cooling process leads to non-homogenous material solidification across the pipe wall and introduces a residual stress distribution close to that shown in Fig. 2b. The residual stresses value greatly depends on the processing history (rapid cooling leads to high residual stresses). According to the literature data [1,12,13], residual stresses in polyethylene (PE) standardly used pipes varies between 2 MPa an 4 MPa and becomes comparable with the maximal tangential stress (hoop stress) induced by the pressurizing of the pipe, see Fig. 2a. Generally, the nonlinear distribution of the residual stress is often simplified by linear distribution, see Fig. 2c. In the course of actual pipe service the overall tangential stress in the pipe wall is then the sum of the tangential stress induced by the inner pressure p_{int} and the residual stress induced by production technology, see Fig. 2d. If the cooling is applied on both the inner and outer surfaces the residual stress distribution across the pipe wall corresponds to Fig. 2e.

Pipe products are designed for long-term applications (modern PE pipes are guaranteed a lifetime of longer than 50 years) so that the stability of the residual stresses over time is a significant factor. In the paper by Frank et al. [1] 20-30 year old pipes were investigated (pipes from 1988, 1987, 1981, 1976). It was found that residual stresses still remains in old pipes at approximately the same magnitude. Residual stresses in the range of 2 MPa to 4 MPa was observed.

In the present work residual stresses were considered at the lower band of experimentally measured values of maximal tangential stress at about 2.3 MPa. Typical distributions of the tangential stresses across the pipe wall taken from numerical simulations are shown Fig. 3.

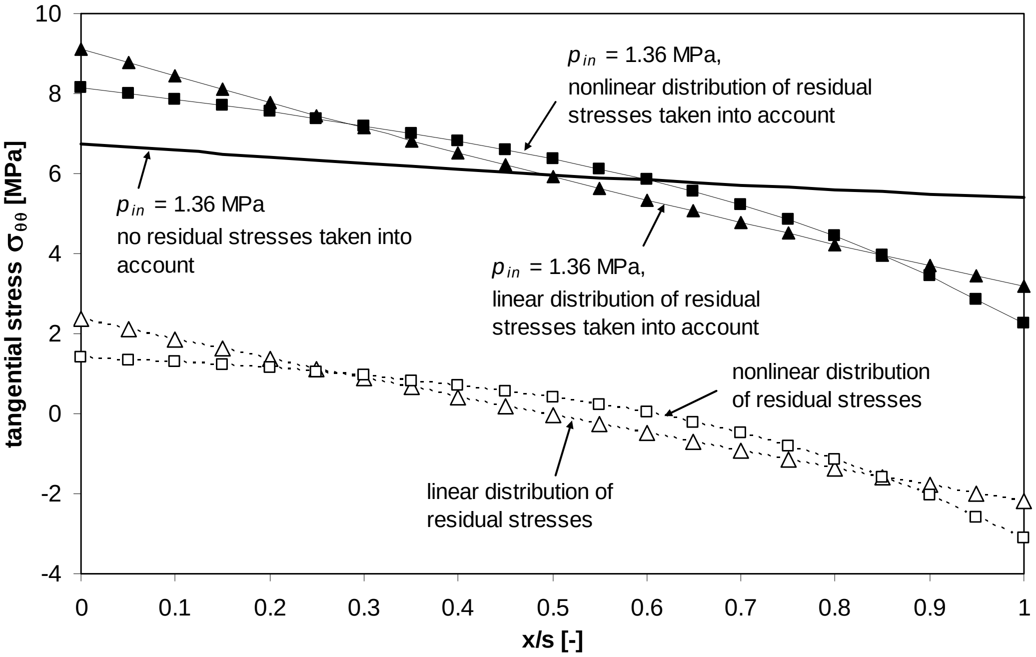

Figure 3. Distribution of the tangential stresses across the pipe wall caused by residual stresses.

NUMERICAL MODEL

A model of a polymer pipe containing a crack was used here in order to quantify the influence of residual stresses on the crack geometry. An axially oriented semi-elliptical crack initiating at the inner pipe wall surface was considered. Making use of the symmetry, it was necessary to simulate only one-quarter of the pipe body. The outer diameter of the pipe studied was $D = 40$ mm with a wall thickness $s = 3.7$ mm. The typical size of the initial defect was estimated on the basis of experimental observations as $a_{in} = 0.1$ mm. Internal pressure p_{int} was varied within the range of 0 and 2.3 MPa corresponding to the hoop stress σ_{hoop} between 0 and 10 MPa. The hoop stress can be calculated as follows:

$$\sigma_{hoop} = p_{\mathrm{int}} \frac{D-2s}{2s}. \qquad (1)$$

The finite element method (FEM), implemented in FE package ANSYS was utilized for the numerical analyses. A 20-node brick 3D iso-parametrical finite element SOLID186 was used for FE mesh generation. Due to the high stress gradient near the crack front the FE mesh was strongly non-homogenously distributed in the body with the finest mesh near the crack front, see Fig. 4.

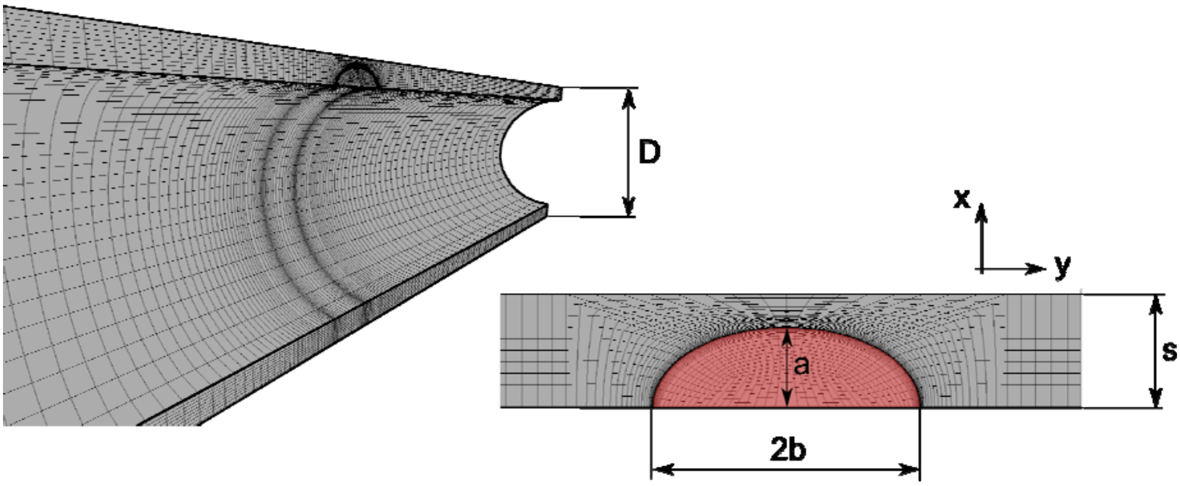

Figure 4. Finite element model of the internally pressurized pipe containing crack.

Creep effects of the pipe material are not considered in this article and for all simulations an elastic isotropic material model is used (corresponding to 20 °C: Young's modulus: $E = 930$ MPa, Poisson's ratio $\nu = 0.33$).

The residual stresses induced by the cooling process were incorporated into the numerical model indirectly using boundary conditions. First, the actual residual stress distribution was obtained by the experimental procedure described in [11]. Based on these results a nonhomogenous distribution of thermal expansion coefficient α across the pipe wall thickness was deduced in this form:

$$\alpha(x) = -1.412\times10^{-5}\left(\frac{x}{s}\right)^3 + 5.020\times10^{-6}\left(\frac{x}{s}\right)^2 - 4.822\times10^{-6}\left(\frac{x}{s}\right) - 9.107\times10^{-7}, \quad (2)$$

where x is a coordinate in the interval <0; s>. Appyling the nonhomogenous distribution of α into the numerical model, the residual stresses can be induced in the pipe wall as shown in Fig. 3 (nonlinear distribution).

As a fracture mechanics parameter describing the stress field around crack front, the stress intensity factor (SIF) was used. For a given crack length *a* the ratio *b*/*a* was iteratively changed in order to obtain a constant stress intensity factor along the crack front. The direct method for estimation of the SIF was used [14]. SIF values were estimated in 25 integration points distributed constantly along the crack front with exception of points close to the free surface. The points close to the free surface are significantly influenced by vertex singularity [15,16] and the correct value of the SIF cannot be calculated there by classical approaches of LEFM.

NUMERICAL RESULTS

The elliptical crack front shape is determined by aspect ratio *b*/*a*. This ratio was numerically estimated for a pipe with residual stresses induced by the manufacturing process. The final aspect ratio *b*/*a* as a function of the relative crack length *a*/*s* is shown in Fig. 5.

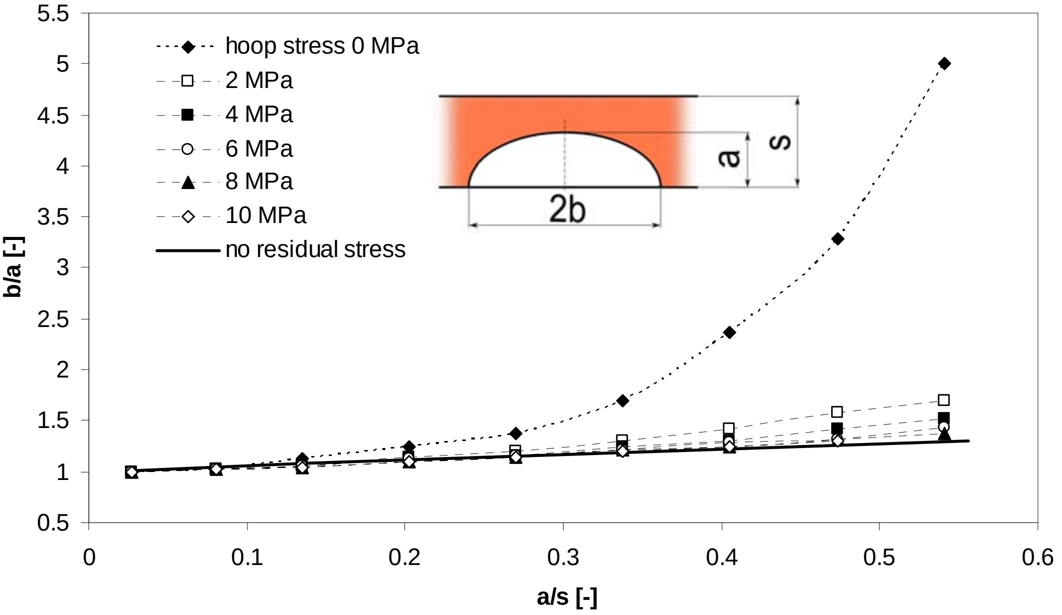

Figure 5. The crack aspect ratio *b*/*a* as a function of the relative crack length *a*/*s* estimated for various levels of hoop stress σ_{hoop}.

It can be seen that the presence of residual stresses infuences the crack front geometry. The crack aspect ratio *b*/*a* is higher than for pure internal pressure for all crack lengths studied. However, for hoop stress greater than 6 MPa the crack shape (*b*/*a*) is approximately similar to that found for pressurized pipes with no residual stresses, see Fig.5.

There exists an equation for estimation of the stress intensity factor (internal pressure only) [6]:

$$K_{I\,\mathrm{int}} = \frac{p_{\mathrm{int}} d}{s} \sqrt{\pi a}\, Y\left(\frac{a}{s}\right),$$

where

$$Y\left(\frac{a}{s}\right) = 0.3417 + 0.0588\left(\frac{a}{s}\right) - 0.0319\left(\frac{a}{s}\right)^2 + 0.1409\left(\frac{a}{s}\right)^3. \qquad (3)$$

The comparison of the present results obtained from a pipe with residual stress and with the relation (3) is shown in Fig. 6.

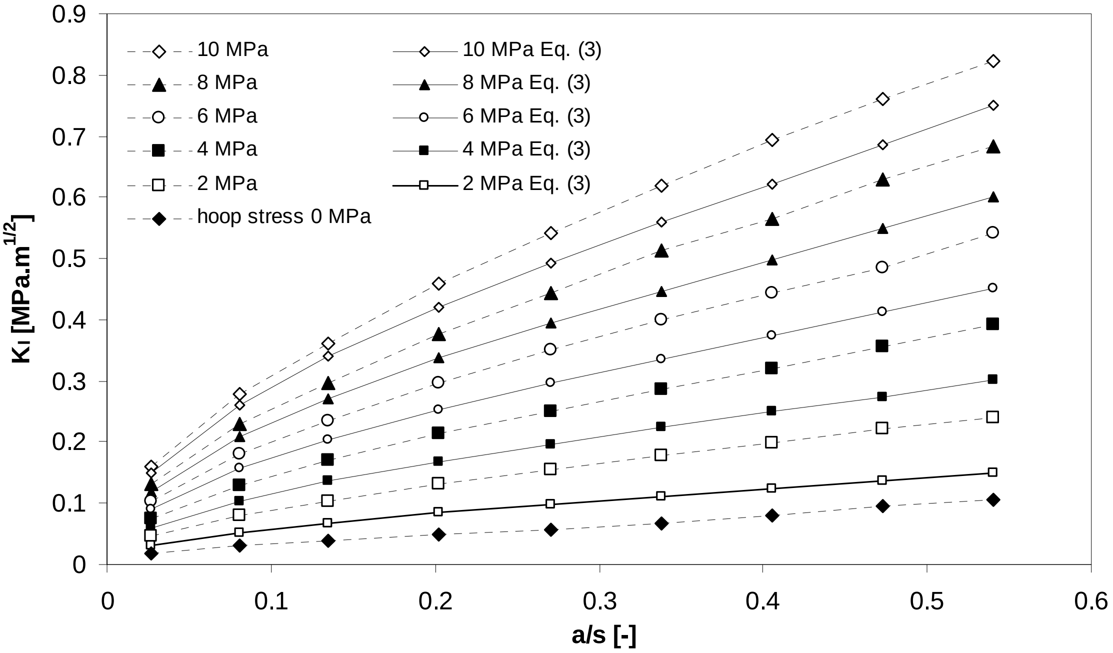

Figure 6. Stress intensity factor K_I estimated numerically for different hoop stress levels with and without residual stresses.

Residual stresses significantly increase the estimated stress intensity factor of cracks in pipes for all loading levels. The increase of K_I seems to be proportional and depends on the additional tangential residual stress. Therefore the modification of the equation (3) including influence of residual stresses can be written in the form:

$$K_{I\,\mathrm{int}}^{residual} = \frac{\left(p_{\mathrm{int}} + p_{\mathrm{int}}^{residual}\right)d}{s}\sqrt{\pi a}\,Y\left(\frac{a}{s}\right),$$

where

$$Y\left(\frac{a}{s}\right) = 0.3417 + 0.0588\left(\frac{a}{s}\right) - 0.0319\left(\frac{a}{s}\right)^2 + 0.1409\left(\frac{a}{s}\right)^3 . \qquad (4)$$

The stress intensity factor estimated in a pipe with residual stresses for hoop stress σ_{hoop} = 0 MPa corresponds aproximately to the stress intensity factor in a pipe with hoop stress equal to maximal tensile stress on the inner surface $\sigma_{\theta\theta}^{residual}$ = 1.4 MPa ($p_{\mathrm{int}}^{residual}$ = 0.29 MPa). It should be noted that the relation (4) is only an approximate estimation of the stress intensity factor. The comparison of numerically estimated stress intensity factors and those calculated using equation (4) is shown in Fig. 7. Good agreement between stress intensity factor values, with a discrepancy smaller than 5%, was found for the pipe geometry considered.

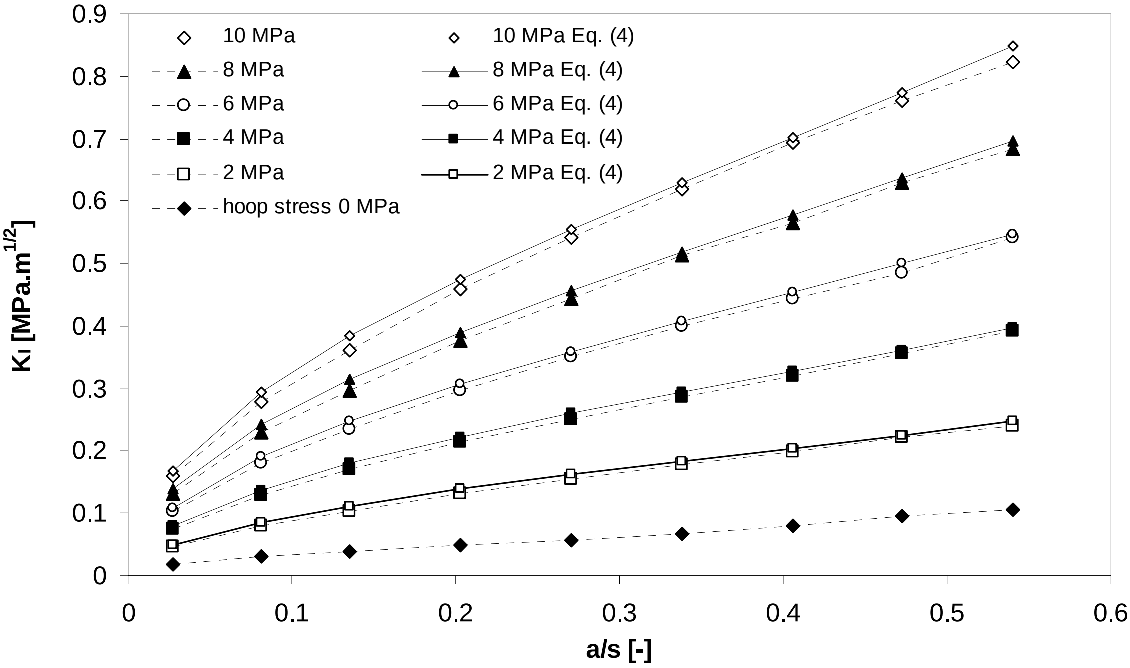

Figure 7. Comparison of the stress intensity factor of the crack in a pipe with the residual stresses estimated numerically and calculated using Eq. (4).

CONCLUSIONS

A numerical study of crack shape development in a polymer pipe with residual stresses was presented here. The crack behaviour was assessed using linear elastic fracture mechanics with the help of the finite element method. The residual stresses corresponding to the experimental data were implemented into the numerical model of the cracked pipe. It was found that the crack shape is influenced by the presence of residual stresses and a significant increase of the stress intensity factor in comparison with a pipe without residual stresses was observed. An approximative equation for the stress intensity factor estimation in the pipe with residual stresses was presented and good agreement with the numerically obtained data was found.

The results presented can be helpful for a rapid lifetime estimation of polyolefin pipelines.

ACKNOWLEDGEMENT

This work was supported by grant P108/12/1560 of the Czech Science Foundation and by the Specific academic research grant of the Ministry of Education, Youth and Sports of the Czech Republic provided to Brno University of Technology, Faculty of Mechanical Engineering No. FSI-J-12-21/1693.

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