20th International Conference
ENGINEERING MECHANICS 2014
Svratka, Czech Republic, 12 – 15 May 2014

FRACTURE MECHANICS ASSESSMENT OF CRACKED WELDED POLYOLEFIN PIPES

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Abstract: *The aim of this paper is to present methodology for estimation of fracture mechanics parameters in polyolefin pipes with an axially oriented crack using three dimensional numerical analyses. Linear elastic fracture mechanics is used for description of fracture behavior. In the paper, three different variants of pipe weld with an internal axial semi-elliptical crack are studied. Numerical models correspond to a cracked pipe containing material nonhomogeneity in the welding area caused by welding process. A critical locations of the crack initiated along the pipe wall is found and the stress intensity factor for such cracks with real crack shape are numerically estimated in these critical locations. The methodology presented here can be used for estimation of residual lifetime of welded polymer pipes containing crack.*

Keywords: Polyolefin pipes, Butt weld, Stress intensity factor, Numerical modeling.

1. Introduction

Nowadays, polyolefin materials are common material in piping industry. Polyolefin materials show high resistance to corrosion, abrasion or chemicals and are therefore suitable for those applications, rather than metallic or ceramic materials. In service, a high functionality is required and thus the pipes are usually designed with a lifetime exceeding 50 years. A new generation of pipes should be able to survive up to 100 years. The pipes are usually connected using butt welding process. Once the welding is finished a material nonhomogeneity takes place in the heat affected zone. Such a change in material properties may accelerate the failure processes. Thus the purpose of this paper is to study the contribution of presence of material nonhomogeneity caused by welding process on the fracture parameter of the crack growing in weld area.

One of the typical failure modes of pressurized polyolefin pipes is quasi-static failure that represents slow (creep) crack growth of a crack initiating at the internal pipe surface. Creep failure testing of the pipes in real time is not practical as the test would be extremely long and expensive. For these reasons numerical models of cracked pipes are being developed in order to study the fracture behavior in reliable time. Even though the material exhibits viscoelastic behavior the slow crack growth regime can be evaluated using linear elastic fracture mechanics (LEFM) approach as the plastic zone in the vicinity of the crack is small and the crack growth rate is slow.

2. Numerical Model

For finite element calculations (FE) of polyolefin pipes a three dimensional model has been developed using the commercial package ANSYS. The pipe dimensions used in the calculations were: outer pipe diameter d = 125 mm and pipe wall thickness s = 7.4 mm.

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The pipe was loaded by an internal pressure $p_{int} \approx 0.8$ MPa acting at both inner pipe surface and crack faces that results in hoop stress of $\sigma_{hoop} = 6$ MPa.

A distribution of Young's modulus in the welding area can be roughly estimated based on the micro-indentation tests along the pipe weld (Lach et al., 2013). The distribution of Young's modulus along the weld can be modeled by the double power-law function (Chi and Chung, 2003) as follows:

$$E(z) = h_1(z)E_{max} + [1 - h_1(z)]E_{min} \text{ for } 0 \le z \le w/2,$$
$$E(z) = h_2(z)E_{max} + [1 - h_2(z)]E_{min} \text{ for } w/2 \le z \le w, \quad (1a)$$

where function $h_{1,2}(z)$ are:

$$h_1(z) = \frac{1}{2}\left(\frac{z}{w/2}\right)^p \quad 0 \le z \le w/2,$$
$$h_2(z) = 1 - \frac{1}{2}\left(\frac{w-z}{w/2}\right)^p \quad w/2 \le z \le w; \quad (1b)$$

and where p is an exponent describing the change of material properties and w is the half-width of the weld region, see Fig. 1. Based on experimental results, performed on the same pipe geometry as analysed in this paper, the exponent $p = 2$ and the width of the weld region $2w = 14$ mm were considered for the numerical analyses. The ratio E_{max}/E_{min} corresponds mainly to pipe materials being welded, e.g. polypropylene pipes exhibit ratio $E_{max}/E_{min} = 1.32$. The Young's modulus of the base pipe material was considered as $E_{min} = 180$ MPa (corresponds to working temperature of 80°C). The Poisson's ratio of $\nu = 0.35$ has been kept constant along the weld.

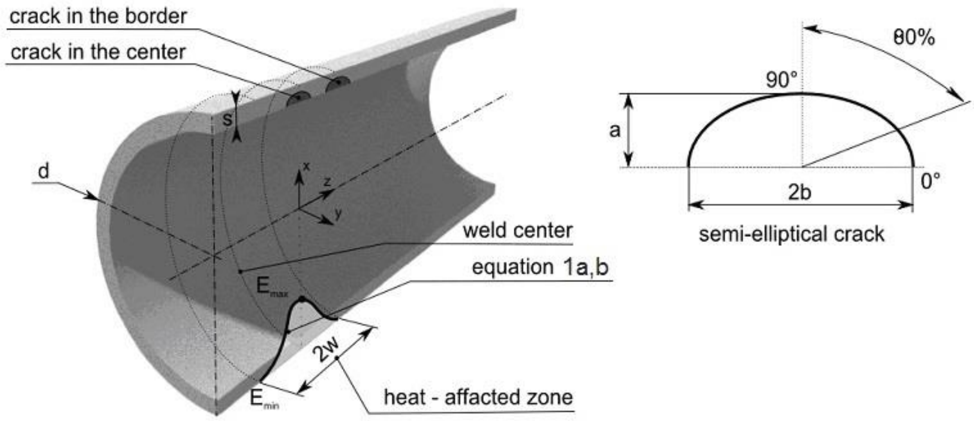

Fig. 1: Scheme of the pipe with a crack considered in the work.

In this study, three different models of the cracked welded pipe have been compared:

- Homogeneous pipe with a crack (PIPE 1),
- Nonhomogeneous pipe weld with a crack in the center of the weld (WELD 1),
- Nonhomogeneous pipe weld with a crack in the border of the weld (WELD 2).

For the homogeneous pipe only the value of E_{min} was considered for the whole numerical model. A preview of finite element mesh with a detail of mesh refinement near the crack front is shown in Fig. 2.

Due to existence of two planes of symmetry only one-quarter of the welded pipe was evaluated in the case of PIPE 1 and WELD 1 model. Due to the crack not lying in the center of the weld, only one plane of symmetry exists for WELD 2 model so that one-half of the welded pipe was considered. The finite element mesh was created by 20-nodes iso-parametrical quadratic element (denoted by number 186 in ANSYS) taken for the calculations and the density of mesh used was depending on the crack length varying from 550 000 to 650 000 elements in the first two cases and about twice as much in the third case. The highest mesh density was concentrated near the crack front in order to describe the stress state near the crack front properly.

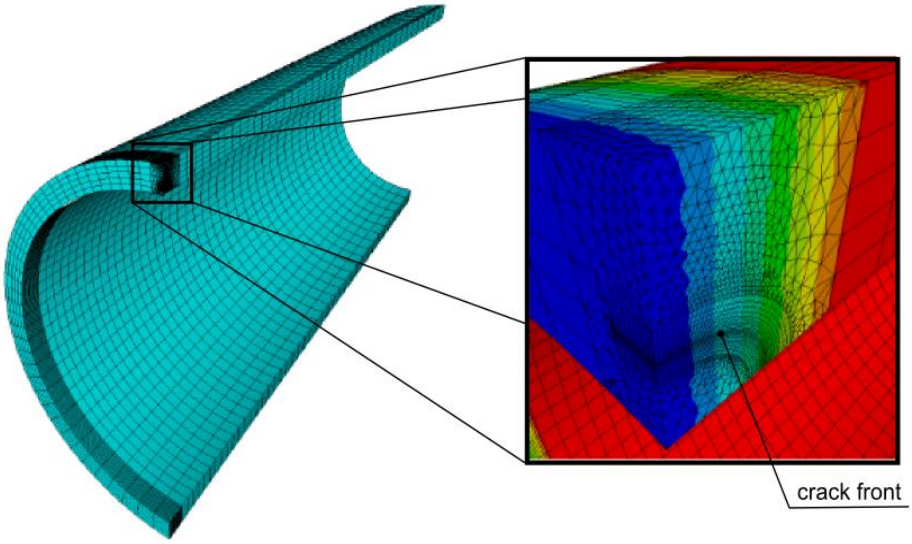

Fig. 2: Finite element mesh with a detail of mesh refinement near the crack front (colors represents different material properties in weld area).

The stress intensity factor for different crack lengths was numerically estimated, from which the lifetime of the pipe can be estimated. The stress intensity factor was evaluated using so called direct method, which is based on extrapolating the opening stress values to the crack tip. It should be mentioned that a few points closest to the crack front are influenced by the numerical error and should be omitted from the extrapolation. To get closer to the real crack propagation a real crack front shape can be found using numerical methods. For a general case of the semi-elliptical crack in the body the distribution of the stress intensity factor (SIF) over the crack front is not constant. It can be assumed the real crack propagates in the continuum when the distribution of the SIF is constant along the crack front. It is possible e.g. to estimate the SIF in 30 points along the crack front and change the aspect ratio of the semi-elliptical crack shape in order to find the real crack front shape. However, the extrapolation paths along the crack front should not be close to the free surface of the body. The reason for this is the vertex singularity (Bažant et al., 1979; Pook, 1994; Hutař et al., 2009) near the free surface that significantly changes the stress field in the vertex point at the free surface so that SIF cannot be estimated correctly by classical approaches of LEFM. Hutař et al., 2011 published an approximative relation for the development of the semi-elliptical crack front in the homogenous polymer pipe as follows:

$$b = a\left[-0.1936\left(\frac{a}{s}\right)^2 + 0.6628\left(\frac{a}{s}\right) + 1.0919\right], \tag{2}$$

where a and b are lengths of major and minor axis of the ellipse representing the crack front shape, see Fig. 1. The crack front shape determined by Eq. (2) is quite similar to those crack front shapes numerically estimated using to the procedure described above for all studied locations of the crack.

3. Results

The stress intensity factor has been numerically estimated for a cracked polymer pipe welds for various position of the crack initiation. An initial defect of 0.1 mm has been considered. The change of the crack front shape during the crack growth was also taken into account. The comparison of stress intensity factor estimated for various crack positions is shown in Fig. 3. An approximative relation for calculation of the stress intensity factor in internally cracked pressurized polymer pipe found in (Hutař et al., 2011) in the following form was used for comparison:

$$K_I = \frac{p_{int} d}{s}\sqrt{\pi a}\left[0.3417 + 0.0588\left(\frac{a}{s}\right) - 0.0319\left(\frac{a}{s}\right)^2 + 0.1409\left(\frac{a}{s}\right)^3\right]. \tag{3}$$

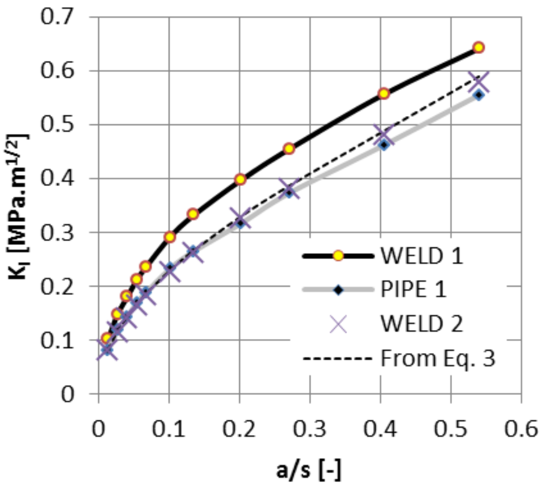

Fig. 3: SIF estimated for different crack position in the weld.

The obtained results of the SIF for the homogeneous pipe are in a very good agreement with Eq. (3) as the maximum error is less than 5% for crack length ratio $a/s = 0.5$. This implies that the numerical model gives sufficient accuracy for subsequent analyses containing nonhomogenous distribution of Young's modulus in the weld area.

In the case of models of cracked pipe weld (WELD 1 and WELD 2) the SIFs were estimated in the deepest point of the crack and the crack front shape was considered to fulfill Eq. (2). For the crack in the border of the weld (WELD 2) values of SIF are very similar to those estimated on homogeneous pipe with the crack. Concerning the crack in the center of the weld it has been found that the SIF is significantly increased due to the material nonhomogeneity and it is therefore the most critical position of an axially oriented crack in the welded pipe.

4. Conclusions

The work presented here describes numerical analysis of axially oriented cracks in polyolefin pipes and evaluates the contribution of material nonhomogeneity as a consequence of butt welding process on fracture parameters. The developed three-dimensional model demonstrated capability to predict correctly the stress intensity factor for pressurized cracked polymer pipe weld. It can be concluded that positive Young's modulus ratio E_{max}/E_{min} results in increase of the SIF values in comparison with a cracked homogeneous pipe. From the performed calculations it may be also concluded that the closer the crack to the weld center is the more critical configuration it produces.

The results obtained in the paper may be used to an estimation of critical crack length or lifetime of internally pressured welded pipes with axially oriented cracks subjected to quasi –brittle failure mode.

Acknowledgement

This work was supported through the grant P108/12/1560 of the Czech Science Foundation and by the Ministry of Education, Youth and Sports of the Czech Republic throughout the Project No. CZ.1.07/2.3.00/30.0063 "Talented postdocs for scientific excellence in physics of materials".

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