The Influence of Different Notches on Fatigue Lifetime of Round Bar Specimens Made of HDPE

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Abstract. *The presented paper introduces an approach for fatigue lifetime predictions of notched round bar specimens made of HDPE. This approach uses axial stress distribution calculated from finite element analysis and experimental fatigue data. The fatigue results obtained experimentally on the round bar specimens with "v" notch with radius* $R = 0.4$ mm *and extremely sharp notch are used for a determination of averaging distance. The averaging distance is applied to specimen with different notch radius for determination of its fatigue lifetime. The fatigue lifetime prediction of a specimen with notch radius* $R = 0.1$ mm *is performed. These fatigue lifetime predictions are compared to experimental fatigue data.*

Keywords

Notches, fatigue, lifetime prediction, HDPE, critical distance

1. Introduction

High-density polyethylene (HDPE) is one of the most demanded polymer materials due to its various properties. Thus, it has found practical applications in different industry sectors, such as automotive, buildings and constructions, chemical industry, electrotechnics, or food industry [1]. These components often have complex shapes with different stress concentrators (notches) and are exposed to variable loading causing premature fatigue failure. To ensure its safe use, it is necessary to study the influence of notches on fatigue lifetime by experimental measurements as well as to have the ability for accurate lifetime prediction.

In the last several decades, a few methods describing different notch types and their influence on the fatigue lifetime of specimens have been published. Among these methods belong concepts of the Theory of critical distances (TCD) [2, 3, 4, 5]. These methods are based on a length parameter that can be used for capturing and predicting the influence of a notch shape on a lifetime of a specimen. They have been applied on different materials such as rocks [3], fibre composites [4] and metallic materials [6]. However, application of TCD approaches on semi-crystalline polymers like HDPE has not been studied yet.

This research is focused on fatigue testing of notched round bar specimens made of HDPE and the evaluation of the experimental fatigue data by a modified approach of TCD [5]. This approach takes advantage of axial stress distribution around notches that is calculated by finite element analysis (FEA) and experimental fatigue data to determine a length parameter. This parameter is used for fatigue lifetime predictions of notched specimens with various notch radii.

2. Experimental tests

The cylindrical specimens with a circumferential notch in the middle are used for the experimental measurements. The specimens are made of blow-molded type of HDPE and are machined from compression molded sheets with a thickness of 20 mm. The final dimensions of the specimens are: diameter 14 mm, length 100 mm, notch depth 1.5 mm. In total, three types of notches are machined: "v" notch with radius of 0.4 mm; "v" notch with radius of 0.1 mm and extremely sharp notch representing a crack, see Fig. 1.

All uniaxial fatigue tests are performed using the computer-controlled testing machine INSTRON E3000 with a sinusoidal loading at a frequency of 10 Hz and at room temperature 23°C. The loading is controlled by force and characterized by maximum force $F_{\max}$, stress asymmetry ratio $(F_{\min}/F_{\max})$ is 0.1.

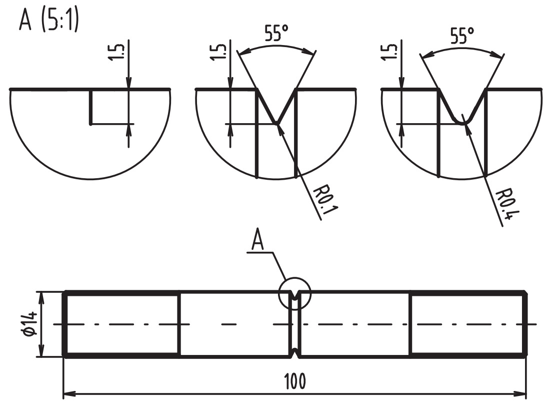

Fig. 1: Geometry of notched specimens: sharp notch representing a crack, $R = 0.1$ mm, $R = 0.4$ mm

3. Finite element analysis

In order to predict lifetime of a specimen by TCD, it is necessary to calculate axial stress distribution. This is done via numerical modeling by finite element analysis in software ANSYS. The specimen's geometry allows using one plane of symmetry and axisymmetry to reduce the calculation time, so only a 2D numerical model (a quarter of cross-section) is created. Elements Plane 183 are used for meshing. The axial stress is plotted along a path r, which is a line going from the notch tip to the centre of specimen, see Fig. 8.

4. Approach description

The approach is based on the averaging critical distance L_c. This distance is used in axial stress distribution for fatigue lifetime description of notched specimens. The averaging distance depends on number of cycles to fracture and is determined from experimental S-N curves of specimens with crack and notches with radius $R = 0.4$ mm. This averaging distance can be used for fatigue lifetime predictions of notched specimens with various radii, in this study, the critical distance is applied on "v" notched specimens with radius $R = 0.1$ mm. The process of fatigue lifetime prediction is summarized in following points.

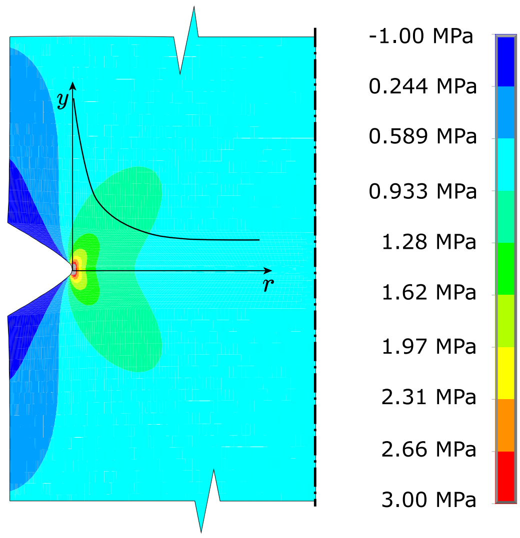

Fig. 2: FEA, Axial stress distribution around a notch tip with $R = 0.1$ mm

1. First, two types of notches in the round bar specimens are tested - "v" notch with radius $R = 0.4$ mm and extremely sharp notch representing a crack. These data were approximated by S-N curves, see Fig. 3.

2. Axial stresses σ_{y} in tested specimens corresponding to 640 000 number of cycles are determined using FEA, see Fig. 4. This number of cycles is selected, because there is enough fatigue data from both experimental curves, and is indicated by black line in Fig. 3.

3. Average stress over the distance from the notch tip $\overline{\sigma_{\mathrm{y}}}(r)$ is determined, see Eq. 1 and Fig. 5. The coordinates of point, where these two lines of average axial stress cross, represent averaging critical distance $L_{\mathrm{c}} = 0.18$ mm and average stress over the critical distance $\overline{\sigma_y}(L_{\mathrm{c}}) = 44.76$ MPa.

$$\overline{\sigma_{\mathrm{y}}}(r) = \frac{1}{r}\int \sigma_y \, dr \qquad (1)$$

4. Averaging distance L_c is applied on different notch radius. Using FE analysis, axial stress distribution of specimen with notch radius $R = 0.1$ mm is determined, see Fig. 6. The averaging distance is applied and average axial stress over the critical distance $\overline{\sigma_y^*}(r = L_{\mathrm{c}},\ R = 0.1 \text{ mm}) = 3.4465$ MPa is found, see Fig. 7. σ_y^* is axial stress calculated for the applied nominal stress $\sigma_{y,nom} = 1$ MPa. $\overline{\sigma_y^*}$ is average axial stress calculated for the applied nominal stress $\sigma_{y,nom} = 1$ MPa, for this reason units are $[\frac{MPa}{MPa} = 1]$.

5. Fatigue lifetime prediction of specimen with notch radius $R = 0.1$ mm corresponding to 640 000 number of cycles is then calculated from Eq. 2, Eq. 3.

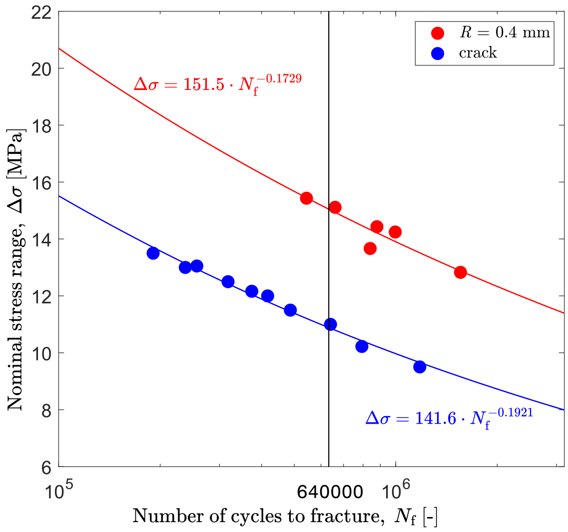

Fig. 3: Experimental fatigue data

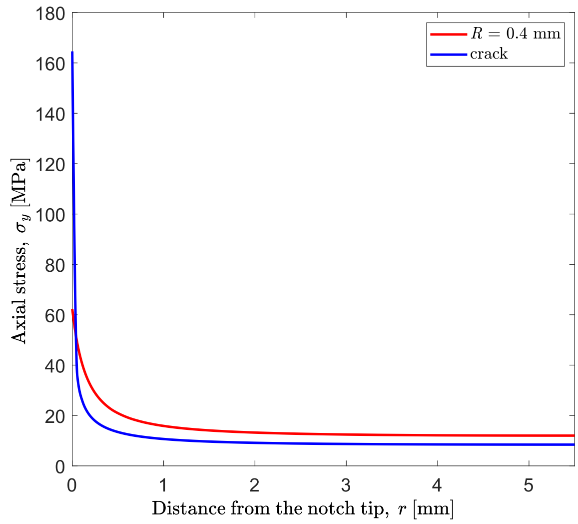

Fig. 4: Axial stress corresponding to 640 000 cycles

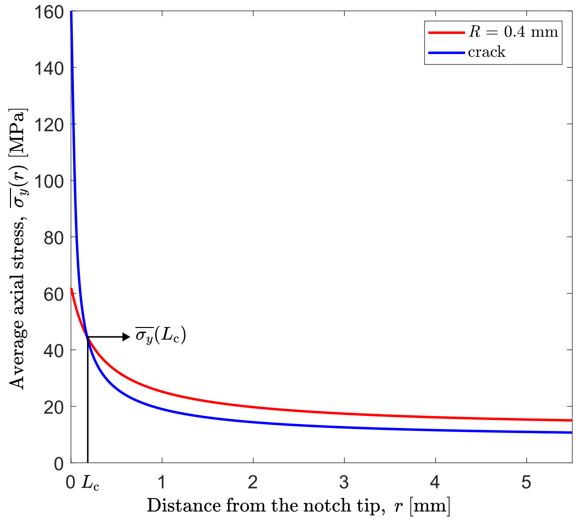

Fig. 5: Average axial stress corresponding to 640 000 cycles

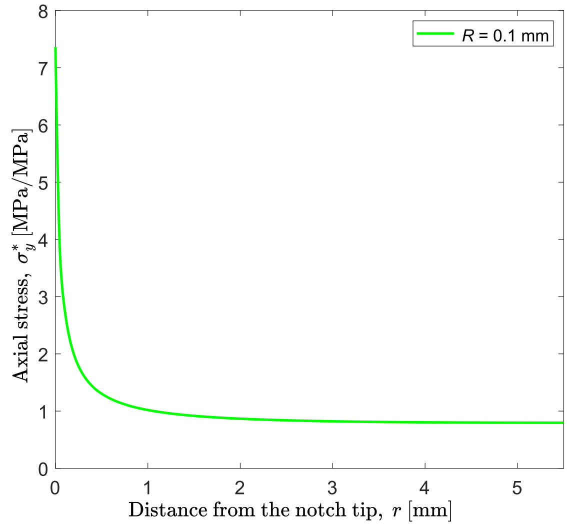

Fig. 6: Axial stress, $\sigma_{y,nom} = 1$ MPa

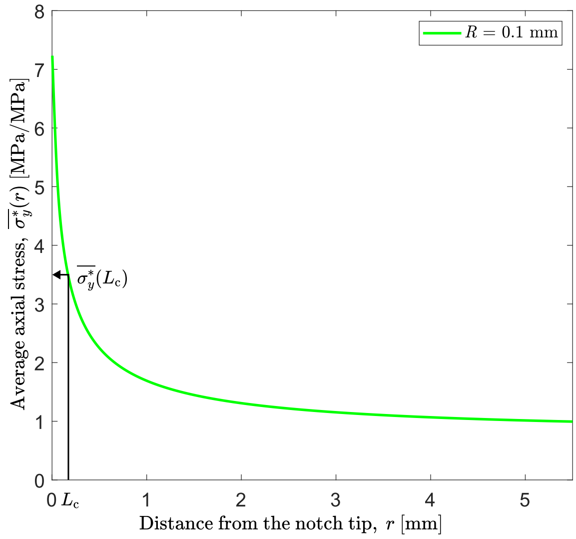

Fig. 7: Average axial stress, $\sigma_{y,nom} = 1$ MPa

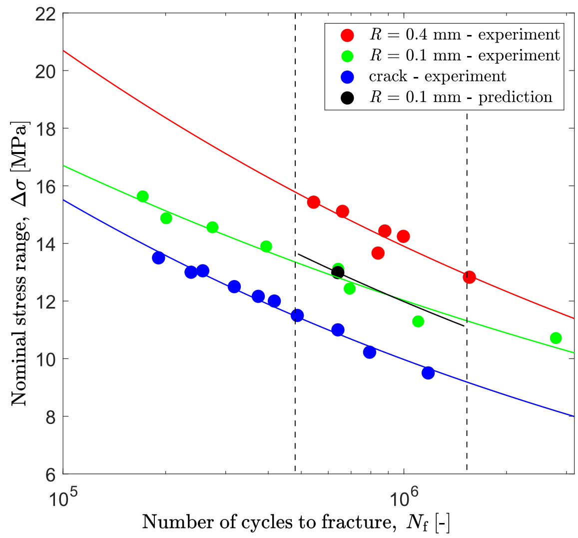

Fig. 8: Fatigue lifetime prediction and experimental data

$$\Delta\sigma_{\text{pred.}}^{R=0.1} = \frac{\overline{\sigma_y}(L_c)}{\overline{\sigma_y^*}(r = L_c,\ R = 0.1\ \text{mm})} \quad (2)$$

$$\Delta\sigma_{\text{pred.}}^{R=0.1} = \frac{44.76}{3.4465} = 12.99\ \text{MPa} \quad (3)$$

6. The whole process of calculation can be repeated for each number of cycles to failure. The another easier engineering way to obtain predicted S-N curve comes from eq. 4. This equation uses ratio between the known predicted point and the experimental S-N curves of specimens with crack and notch radius $R = 0.4$ mm.

$$\frac{\Delta\sigma^{R=0.1}(N_{fi}) - \Delta\sigma^{crack}(N_{fi})}{\Delta\sigma^{R=0.4}(N_{fi}) - \Delta\sigma^{crack}(N_{fi})} = \text{const.} \quad (4)$$

7. Fatigue lifetime prediction (black) and experimental data (green) are compared, see Fig. 8. The fatigue liffetime prediction of specimen with notch radius $R = 0.1$ mm corresponding to 640 000 cycles is 12.99 MPa and experimental result is 12.81 MPa. They differ by 0.18 MPa, what is 1.4 % of experimental result. Thus, the methodology is in good agreement with experimental results.

5. Conclusion

The paper introduces the approach for fatigue lifetime predictions of notched specimens made of HDPE. This approach uses critical averaging distance and average axial stress over this distance.

The critical distance is calculated from experimental fatigue data of two types of notched specimens (notched specimens with radius $R = 0.4$ mm and specimens with sharp notch representing crack) and corresponding axial stress distributions. The averaging critical distance depends on number of cycles to failure.

In this study, the procedure of fatigue lifetime predictions is used for prediction of specimen with “v” notch radius $R = 0.1$ mm close to 640 000 number of cycles. Although, this approach can be applied at different number of cycles to fracture and various notches with different notch radii.

Fatigue lifetime predictions of specimens with notch radius $R = 0.1$ mm were compared to experimental fatigue data. The biggest difference between prediction and experimental approximation is 0.3 MPa. This difference is considered to be unimportant. However, more precious prediction of the lifetime can be obtained by determination of the averaging distance for whole range of N_f.

The averaging distance corresponding to 640 000 cycles to fracture was 0.18 mm. The critical value is in an agreement with D. Taylor’s study [7], where amorphous polymers can be predicted using the TCD with values of the order of 0.1 mm.

Presented approach reduces the need to perform fatigue tests of notched specimens made of HDPE and saves testing time.

Acknowledgment

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