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FACTORS INFLUENCING CRB TEST RESULTS

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Abstract: This contribution deals with simulation of fracture behaviour of specimens for CRB (cracked round bar) test. These specimens are used for accelerated testing of polymer materials' performance for piping applications. The CRB test is one of the most effective methods of testing due to use of cyclic loading instead of more common static force. However, in some cases the CRB specimens' fracture surfaces come out asymmetrical. With the use of FEM simulation of the crack propagation in CRB specimens, the influence of this asymmetry on the results of CRB test is investigated.

Keywords: polymer pipes; polyethylene, CRB test; fracture surface; FEM simulation

1 Introduction

One of the most important properties of any polymer pressure pipe (e.g. for water or gas transportation) is its expected lifetime. There is a couple of methods for estimating the lifetime expectancy of the pipe. So far, extrapolation of hydrostatic pressure test results has been the most common, but it is not effective for testing new pipe material grades (e.g. the PE100RC) with enhanced resistance to crack growth, because it takes too much time. Therefore, different approach has been developed. It has been established that the most frequent mechanism of pipe failure is the slow crack growth (SCG) [1, 2]. This mechanism can be characterized by cracks growing very slowly through the pipe wall with almost no plastic deformation. The SCG crack growth rate in a specified material can be measured by tests on notched specimens. If the measured crack growth rate is plotted in a log-log plot versus corresponding stress intensity factor, it creates a typical linear dependency that can be described by a modified version of Paris-Erdogan equation

$$\frac{da}{dt} = A\left(K_{I,max}\right)^m \tag{1}$$

where *da/dt* is the crack growth rate, $K_{I,max}$ is the stress intensity factor and *A* and *m* are material constants. It is then possible to obtain the lifetime estimation by the combination of FEM simulations (to obtain the stress intensity factors dependency in a real pipe) and integration of the modified Paris-Erdogan equation [3].

The tests on notched specimens are faster than the hydrostatic pressure test as they are. To be even more effective, the crack growth is accelerated in various ways – e.g. by heating the environment as in the case of PENT (Pennsylvania Edge Notch Tensile) test or adding a chemical agent as in the case of FNCT (Full Notch Creep Tensile) test. So far, the two mentioned tests, PENT and FNCT, have been also the most popular among the accelerated test methods. However, CRB (cracked round bar) test has been gaining a lot of popularity recently.

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1.1 CRB test and a problem of fracture surface asymmetry

CRB (cracked round bar) test is a rather new method of accelerated testing of polymer materials for piping applications [4, 5]. It uses cylindrical specimens with a razor-sharp notch circumferential in the middle (Figure 1a). These specimens are not loaded by a static force, but by cyclic force, which accelerates the crack growth. The number of cycles to failure is measured. Based on the elapsed number of cycles at a certain load, the materials can be ranked simply. The greatest advantage of this test is that it can be carried out at room temperature without any special environment and it is the fastest of all the accelerated test methods. The main disadvantage of this test is that monitoring the crack growth in order to obtain crack growth rate is quite difficult, because the crack length cannot be seen directly due to the cylindrical shape. This crack length has to be calculated from COD measured by extensometers mounted on the specimen (Figure 1b).

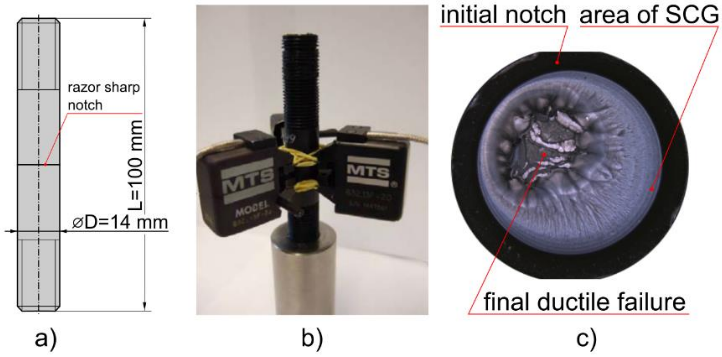

Figure 1: Scheme of the CRB specimen (a), experimental setup with extensometers (b) and fracture surface of CRB specimen (c).

In some cases, cracks in CRB specimens grow faster on one side of the specimen than on the other. This asymmetry is noticeable on the resultant fracture surface (Figure 1c). The cause of the asymmetry can be the asymmetrical loading of the specimen in the testing device, residual stress or inherent asymmetry of the notch. As the crack grows asymmetrically, the measured crack growth rate might be influenced. In this article, the residual stress as a possible cause for the crack asymmetry is investigated. Using FEM simulation of the CRB test, the influence of the asymmetry on the results of CRB test is determined. All the following results were obtained by experiments on specimens made of polyethylene for piping applications.

2 Residual stress in CRB specimens

The CRB specimens can be manufactured either from specially extruded plates or directly from the wall of the tested pipe. If they are made directly from the pipe wall, there is a problem with axial residual stress, that is present in the pipe wall. When the specimen is cut out of the pipe, the axial residual stress relaxes, which causes the specimens to bend. The deformed specimens are then turned on a lathe to form a cylinder. Usually, these specimens remain slightly deformed (see Figure 2). In the testing device, they are straightened by the loading force, which causes the asymmetry in loading and subsequent asymmetrical crack growth. Four CRB specimen was examined to find out the residual stress causing their deformation. The examined specimens were manufactured directly from the pipe wall. Their deformation was measured and axial residual stress present in these specimens was determined by calculation.

Figure 2: Photo of the CRB specimen manufactured from the pipe wall. The specimen is noticeably deformed.

To calculate the axial residual stress causing the measured deformation of the CRB specimen, simple FEM model of the CRB specimen was created. The residual stress was included in the model by defining initial stress state of the elements. Deformation of the model caused by the residual stress was calculated. Then, the residual stress magnitude was changed in a few iterations, until the calculated deformation matched the measured value. The shape of the distribution was assumed to be similar to previously found distributions of axial residual stress in PE pipes [6]. It can be characterized by the following exponential equation:

$$\sigma_{aRES}(x_r) = c_1 + c_2 e^{3.2x_r} \tag{2}$$

where x_r stands for relative position in the pipe wall (or specimen), $x_r = 0$ means the inner surface of the pipe wall, $x_r = 1$ means the outer surface. c_1 and c_2 are constants. In general, the obtained distributions of axial residual stress in CRB specimens are significantly lower than the original distribution of axial or tangential residual stress in a PE pipe, based on previous experiments. See comparison in Figure 3. The highest measured magnitude is approximately 50% of the original value, the lowest is less than 30%. These distributions, the highest and the lowest, were used as an input in further simulations of CRB fracture behaviour.

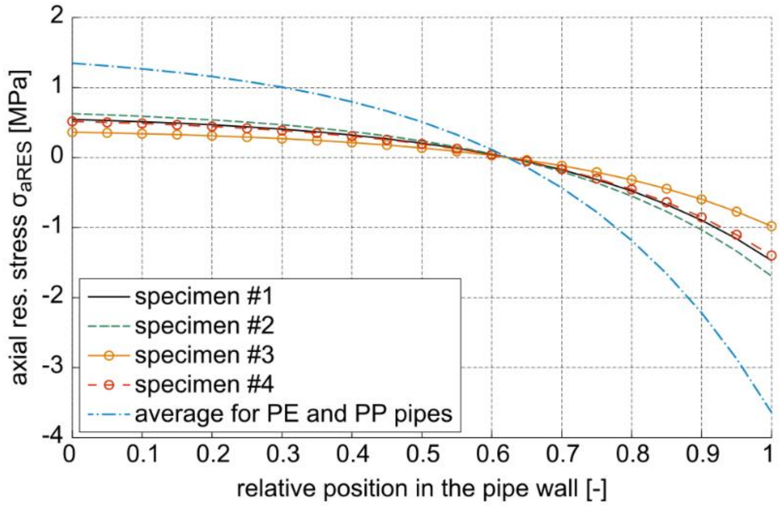

Figure 3: Axial residual stress in four examined CRB specimens compared to an average distribution from previous experiments on PE and PP pipes.

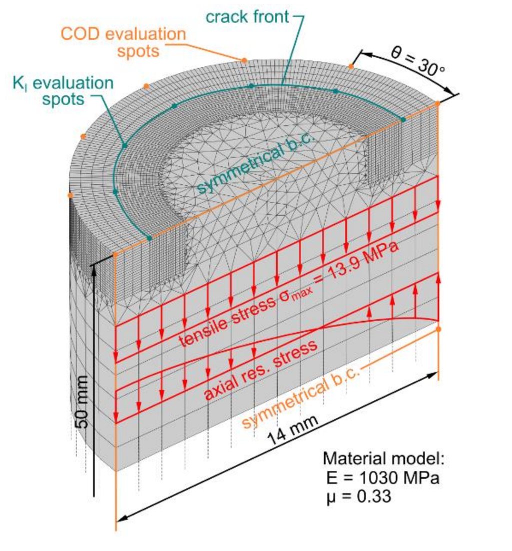

Figure 4: Mesh of the CRB specimen model with loading and boundary conditions.

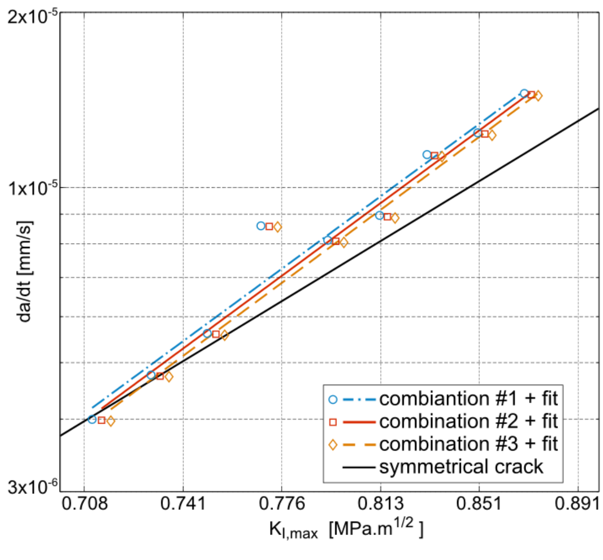

Figure 5: Comparison of detected crack growth rate for asymmetrical and symmetrical crack

3 FEM simulation of CRB test

The aim of numerically simulating the CRB test was to see if the asymmetrical crack growth can significantly influence the results, especially the detected fatigue crack growth rate. Symmetrical model of the CRB specimen was created (see parameters of the model in Figure 4). The model was loaded with a combination of tension and asymmetrical distribution of residual stress. Stress intensity factors were calculated and, based on their magnitude in different spots on the crack front, the next shape of the crack was determined. This way, 10 iterations were carried out and the crack increments were established. It was assumed, that the crack propagates at a rate given by previous experiments on polyethylene. Based on this assumption, time intervals between the crack increments were calculated by integration of modified Paris-Erdogan equation.

COD signals from the edge of the crack were also calculated by the model. Detected crack growth rate was determined from these signals using the same procedure, as in the case of real CRB specimen, see [4]. The detected crack growth rate from the asymmetrically growing crack differs from the originally assumed crack growth rate, because the asymmetrically growing crack causes irregularity in the COD signals. The detected crack growth rate was compared to the crack growth rate detected when the crack grows symmetrically to see if the difference is significant. The symmetrical crack growth rate is identical to the originally assumed one. Also, 3 combinations of extensometer positions (position is described by the angle θ) on the CRB specimen edge were evaluated to see, if positioning the extensometer can influence the results (combination #1 [0° 120° 240°], combination #2 [30° 150° 270°], combination #3 [60° 180° 300°]). Comparison of the results for the case of the highest residual stress distribution in the CRB specimen from the experiment is in Figure 5. The crack growth rates are presented as a dependency on appropriate stress intensity factors value, which is the desired result of the CRB test.

4 Conclusions

A series of experiments and FEM simulations was carried out to find out, if the residual stress might influence the results of CRB tests. Residual stress in CRB specimens was calculated from measured deflections. The obtained residual stress was 30% - 50% of the original residual stress in the PE pipes, from which the CRB specimens are manufactured. these distributions were used in simulations of the actual CRB test. By simulating the asymmetrical crack growth in the CRB specimen caused by the presence of residual stress, a detected crack growth rate was obtained. This detected crack growth was compared to a symmetrical crack growth rate, that would be obtained under ideal conditions. The comparison shows that the detected crack growth is different from the ideal crack growth rate by approximately 15%, which means the residual stress or any asymmetry can cause discrepancy in the results of the CRB test. However, the presented case was the case of the highest residual stress. In the case of the lower residual stress the crack growth rate practically matched the ideal curve, which means that a certain amount of residual stress or asymmetry is tolerable.

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