FRACTURE MECHANICS TESTING OF HIGH DENSITY POLYETHYLENE (HDPE) PIPE MATERIAL WITH COMPACT TENSION (CT) SPECIMENS

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Abstract: The lifetime of polyethylene pipes used for water and natural gas distribution is usually estimated based on relatively long-time creep tests. The pipes fail in service at room temperature and low stress in brittle mode called "long-time brittle failure". In order to economically predict the long term creep performance of HDPE pipes, short term static or fatigue tests are used, in which the crack growth rate is substantially increased. One of the recent tests capable of presenting results useful for HDPE pipe failure prediction is based on the concepts of fracture mechanics. The paper the tests performed on CT specimens cut directly from the HDPE gas pipe in order to determine the fracture toughness the crack propagation rate in fatigue and the crack propagation rate at different loading speeds. The crack propagation speed was monitored by video-controlled technique.

Keywords: polyethylene pipes, crack growth rate, CT specimens, fracture toughness

1. INTRODUCTION

Short term testing represents on economical alternative approach for determining the material characteristics used to predict the life time of High Density Polyethylene HDPE pipe lines. A condition for accelerating the crack propagation rate is to maintain the same failure mechanism, like the stepwise failure mechanism observed in field failures.

In order to predict the long-term creep performance of HDPE pipes, the concept of fracture mechanics received in creasing interest. The estimation of long-term service lives of HDPE pipes lines requires fracture mechanics material characteristics, obtained by applying a standardized test procedure [1-3]. Some of the most important tests characterize the crack initiation stage and the slow crack growth rate [4].

The paper presents the testing procedure for determining the following fracture mechanics material parameters: the fracture toughness, the crack propagation rate for cyclic loading and the crack propagation rate for different loading speeds, using CT specimens.

2. EXPERIMENTAL SETUP

2.1. Material and specimen

The material investigated was a high density grade PE100 polyethylene as pipe with nominal size OD = 355 mm and SDR11, used in medium pressure natural gas distribution.

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The compact tension (CT 100) specimens with geometry presented figure 1 were cut directly from the HDPE gas pipe. The specimens met the ASTM E 399 and ASTM E 647 requirements.

In order to initiate the crack propagation, an initial notch was realized at the bottom of the V-shaped notch by using a razor blade.

The preliminary test indicated that the front of the crack was not linear during propagation. To minimize this effect, V-shaped grooves were cat on both sides of the specimen (see Figure 1).

2.2. Loading device and crack length measurement
The specimens were loaded in a servo-hydraulic testing machine INSTRON 8801 in two ways:
- fatigue testing at a frequency of 5 Hz with a ratio $R=F_{min}/F_{max}$=0,1;
- facture tests with continuously increasing of the load.

Tests were carried out in air, at room temperature.

The load and crosshead displacement were recorded by the computer of the testing machine, while for crack length measurement a video camera was used.

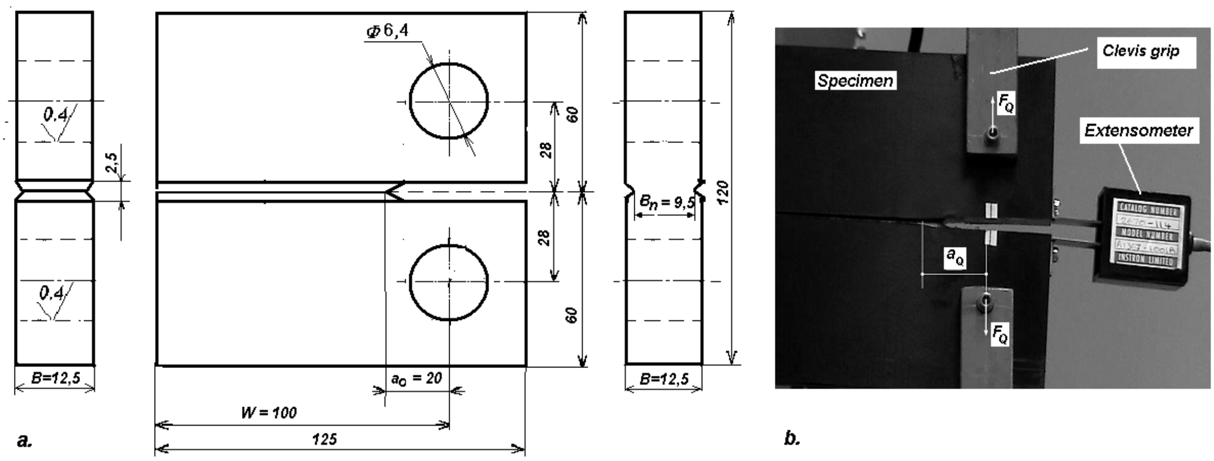

Fig. 1. CT 100 specimen and testing facilities: a – specimen sketch ; b – testing facilities.

3. RESULTS AND DISCUSSION

3.1. Fracture toughness determination
The fracture toughness K_{Ic} is the critical value of the stress intensity factor K_I at the point of instable crack growth.

The fracture toughness was determined according to ASTM E399 and ASTM E1820 using the stress intensity expression under the linear elastic fracture mechanics assumption:

$$K_{Ic} = \frac{F_Q}{\sqrt{B \cdot B_n \cdot W}} \frac{2+\alpha_Q}{(1-\alpha_Q)^{3/2}} (0.886 + 4.64\alpha_Q - 13.32\alpha_Q^2 + 14.72\alpha_Q^3 - 5.60\alpha_Q^4) \qquad (1)$$

In Figure 2 are presented the load-displacement curve and the main characteristics necessary for fracture toughness determination.

The material fracture toughness obtained is K_{Ic} = 0.743 MPa $m^{1/2}$.

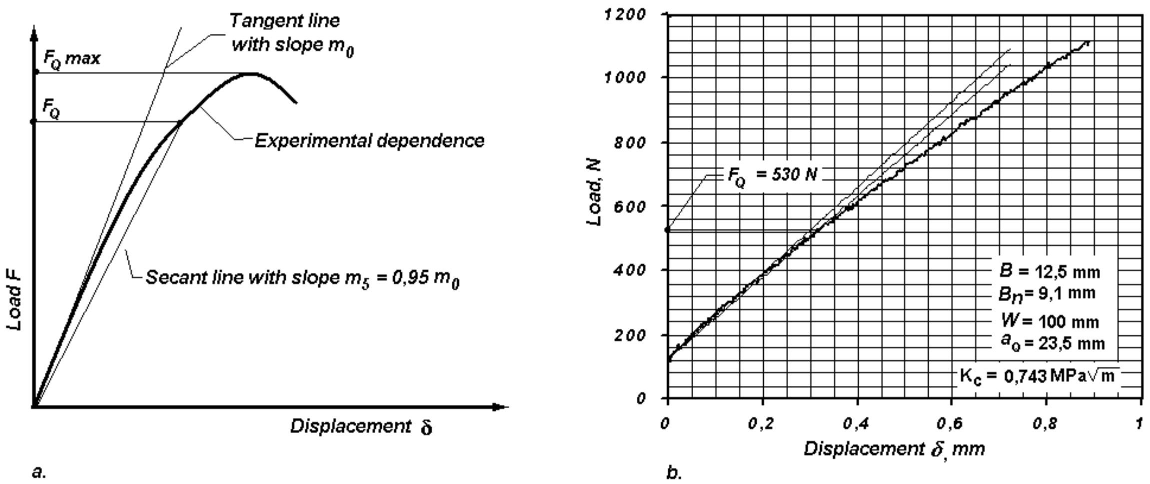

Fig. 2. Experimental fracture toughness determination:
a – principle of load-displacement records; b – experimental data for HDPE.

3.2. Crack propagation characteristics

3.2.1. Fatigue crack propagation rate

Fatigue tests under $R=F_{min}/F_{max}$ = 0.1, F_{max} = 1100 N and frequency f = 5 Hz were performed on two CT 100 specimens in order to determine the rate of fatigue crack growth per cycle, da/dN (a - crack length, N - number of cycles).

After N = 143,000 cycles for the first CT specimen and N = 150,000 cycles for the second CT specimen, the specimens were removed from the fatigue machine, and broken after cooling at −20 ^{0}C in order to analyze the crack tip and to measure the final crack length (see Figure 3).

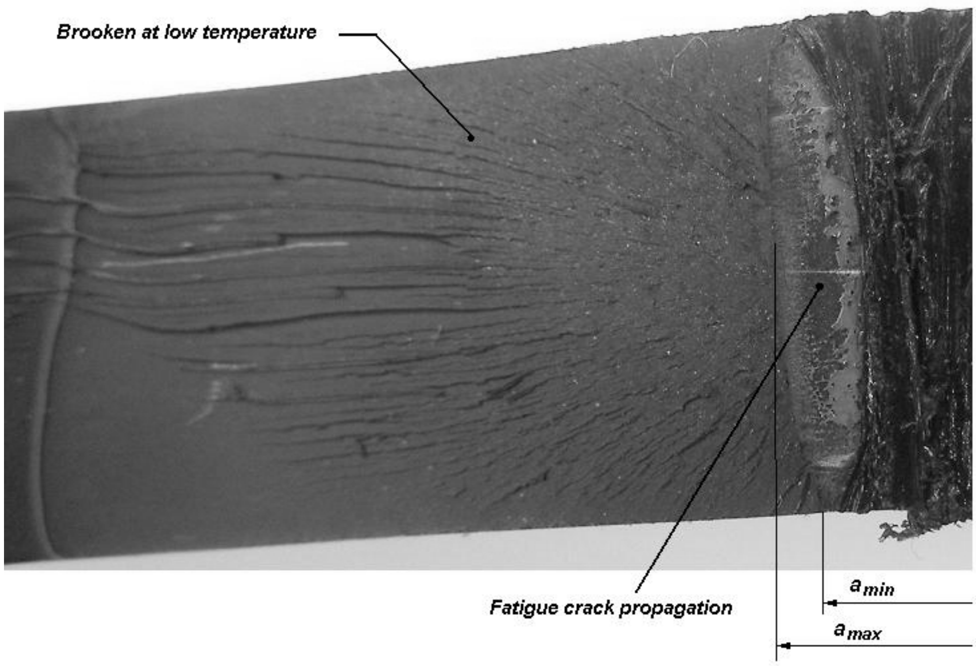

Fig. 3. Final crack length determination.

The average crack propagation rate is da/dN =3.5524 E−05 mm/cycle.

3.2.2. The crack growth rate

The crack growth rate was determined by continuously loading the CT 100 specimens at different loading speeds (1, 2, 25 and 50 mm/min) and measuring the corresponding time dependent displacement and crack length.

Based on these data the dependence stress intensity factor-time and the crack propagation speed (mm/s) are calculated.

Figure 4 shows the records of load, F, crack length, a, and calculated stress intensity factor, K_I plotted against time, for 2 mm/min loading speed.

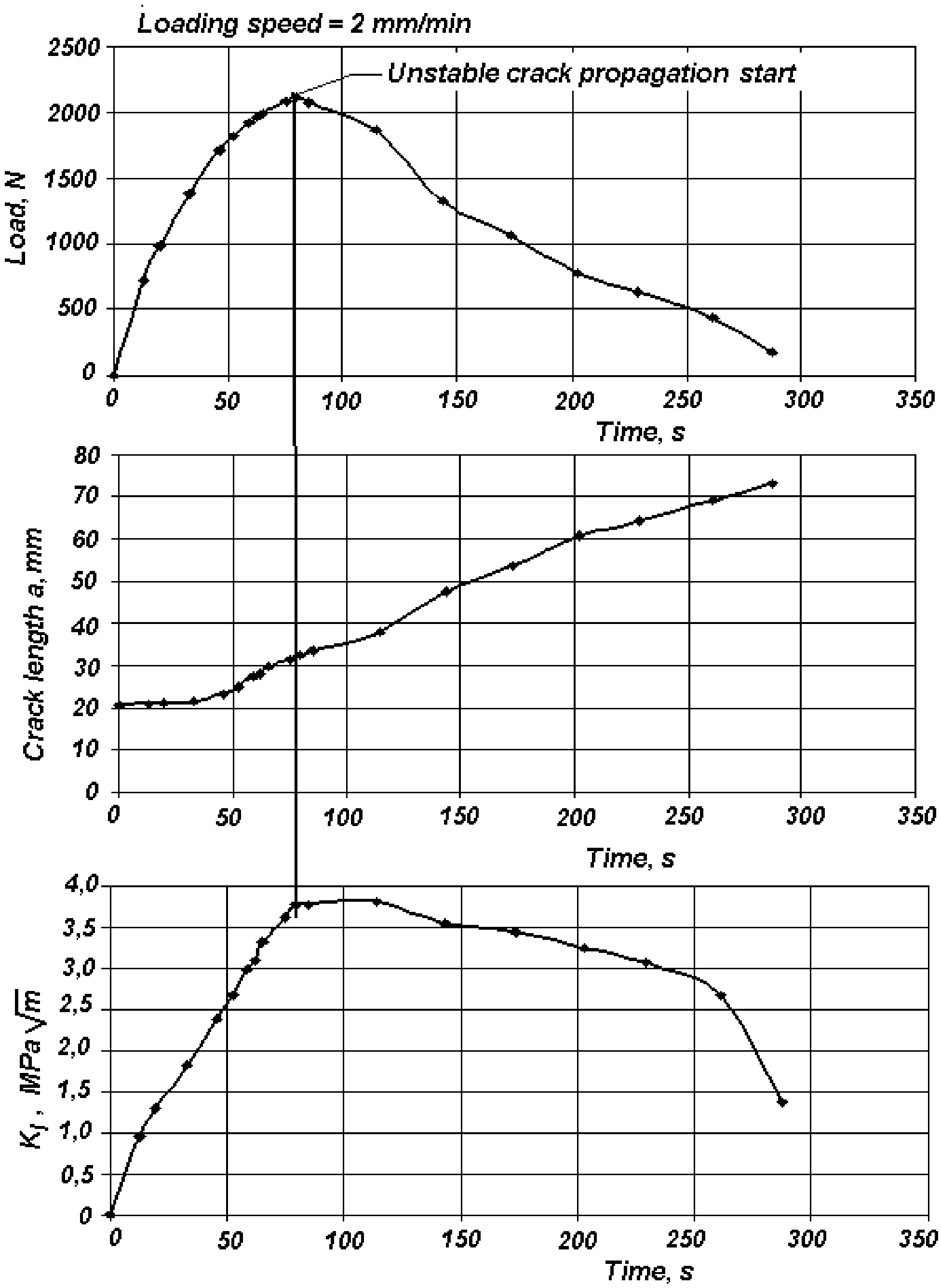

Fig. 4. Load-time, crack length-time and stress intensity factor-time curves for 2 mm/min loading speed.

Based on the observation that the crack length -time dependence is linear, the crack propagation speed and the corresponding maximum stress intensity factors are listed in Table 1.

The log(da/dt) - log K_I plot present a linear dependence (Figure 5), indicating a power law relationship:

$$\frac{da}{dt} = 5.54 \cdot 10^{-8} \cdot K_I^{4.66} \qquad (2)$$

Thus the empirical Paris law is confirmed, with a stress intensity exponent 4,66, in good agreement with other experimental results [5-7].

Table 1 Crack propagation speed and maximum stress intensity factors.

Loading speed, mm/min	da/dt	K_I, MPa $\sqrt{m}$
0.5	0.036330406	2.836281175
1	0.053687284	3.062003667
2	0.086008197	3.276999091
25	0.159827384	3.864322773
50	0.200116337	4.064466278

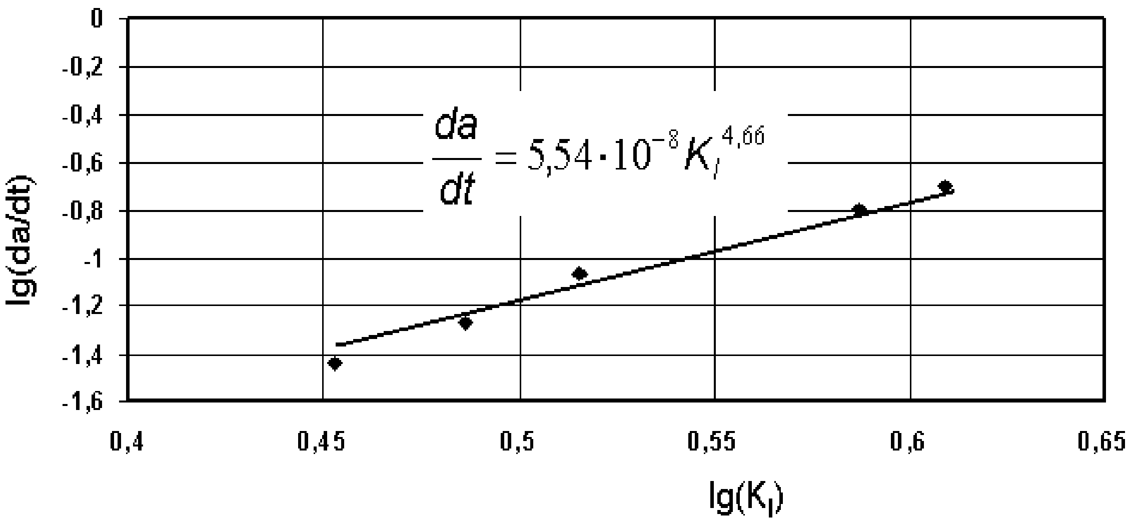

Fig. 5. Crack propagation rate vs. stress intensity factor.

By integrating the equation (2) the lifetime of HDPE pipes with a initial flow (discontinuity) with the dimension a_0, the crack propagation time is :

$$t = \int_{a_0}^{s} \frac{da}{C \cdot K^m} \qquad (3)$$

were s is the thickness of the pipe wall.

4. CONCLUSIONS

A testing method was proposed for crack propagation measurement during fatigue testing and continuously increasing the tensile load on CT 100 specimens.

The fracture toughness, crack propagation rate in fatigue and crack growth speed for PE100 HDPE were determined.

The empirical Paris law for crack growth is verified, offering a means for estimating the total life of a pressurized HDPE pipeline.

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