ISSN 1330-3651
UDC/UDK 621.643.2.028 : 620.169.1

LIFE PREDICTION OF DAMAGED PE 80 GAS PIPES

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Preliminary notes

This paper deals with new approach to life estimation of damaged thick-walled gas pipes made of high-density polyethylene (PE 80). The most common approaches to polyethylene gas pipes durability prediction rely on methods of fracture mechanics, which involve defining the stress intensity factor experimentally. However, such tests are carried out on standardized specimens neglecting the influence of real pipe geometry and processing method. On the other hand, these data are not always available to gas distributors, which are responsible for installed pipelines durability. Investigations based on long-term experiments involving three parameters: pressure, length and depth of initial notch type crack gave empirical mathematical model for life prediction of polyethylene gas pipes.

Keywords: *pipe damages, pipe bursting time, PE 80 pipes*

Predviđanje životnog vijeka oštećene plinske cijevi PE 80

Prethodno priopćenje

U radu je prikazan novi pristup za procjenu preostalog vremena uporabe oštećenih plinovodnih cijevi od polietilena visoke gustoće (PE 80). U praksi se najčešće primjenjuju metode mehanike loma za procjenu trajnosti polietilenskih plinovodnih cijevi koje uključuju eksperimentalno definiranje koeficijenta intenzivnosti naprezanja. Međutim takvi su testovi napravljeni na normiranim ispitnim tijelima pri čemu je zanemaren utjecaj stvarne geometrije i postupak proizvodnje cijevi. S druge strane, podaci o koeficijentu intenzivnosti naprezanja nisu uvijek dostupni distributerima prirodnog plina. Provedbom dugotrajnih ispitivanja temeljenih na distributerima dostupnim podacima: tlaku u cijevima, duljini zareznog oštećenja i dubini zareznog oštećenja dobiven je empirijski matematički model za procjenu preostalog vremena uporabe oštećenih polietilenskih plinovodnih cijevi.

Ključne riječi: *oštećenja cijevi, vrijeme do loma cijevi, cijevi od PE 80*

1
Uvod
Introduction

Increased application of polymer materials for installing various industrial and communal pipelines (such as cold and hot water pipelines, steam pipelines and gas pipelines) puts up the question of system durability before distributors. Therefore, several methods for life prediction of polymer pipes were developed mostly based on methods of fracture mechanics, which involve experimentally defined stress intensity factor. However, in such methods stress intensity factor is determined on standardized specimens neglecting the influence of real pipe geometry and processing method (e.g. properties anisotropy as a consequence of an extrusion process) [1, 2]. Major disadvantage is the fact that methods of fracture mechanics are based on observations of crack developing all over specimen intersection, what cannot be directly applied on damaged polyethylene pipes because when it comes to breaking pipe wall, the pipe becomes useless. Furthermore, information on stress intensity factor is usually unknown to distributors. The only information that distributor really has access to, when perceiving damages on polyethylene pipes, is length and depth of initial notch type crack and gas pressure in pipes. Due to the mentioned, and first of all for practical reasons, obtaining empirical mathematical model and by that new approach based on available and measurable data (length and depth of initial notch type crack and pressure in pipes) for life prediction of damaged polyethylene gas pipes seemed reasonable. Apart from above mentioned influential factors notch type crack direction (axial or radial) also has considerable influence on lifetime of PE gas pipes. Further in text, design and course of the experiment as well as results of investigation on PE 80 gas pipes with axial notches will be considered in particular, although axially and radially cut PE 100 gas pipes were also tested. Experiment was not carried out on PE 80 pipes with radial notches, because depending on control units´ technical limitation it could be carried out only on three different pipe types.

2
Experimental investigation on PE 80 pipes with axial notches
Eksperimentalno istraživanje na cijevima od PE 80 s aksijalnim zarezima

Aiming to obtain an empirical mathematical model for life prediction of PE 80 gas pipes with axial notches, experimental investigation, that lasted more than 2,5 years, was carried out. The influence of initial notch geometry and internal pressure on time to get pipes failed (burst due to internal pressure) was tested in experiment. In such a way, real situation when some accidental cuttings or notch type damages on pipe surface could occur during their mounting into the ground was simulated.

2.1
Design and course of the experiment
Plan i tijek pokusa

Central composite experiment design with three influential factors: initial notch length *A*, initial notch depth *B* and internal pressure *C* was chosen. The above-mentioned factors were chosen based on literature research and experiences in practice.

Central composite experiment design belongs to the group of higher order tests, and is also called response surface methodology. Response surface methodology includes a set of statistical and mathematical methods applied for development, improvement and optimization of process. Measurable value of product or process quality is called response function or shorter response [3].

Figure 1 shows central composite experiment design with three influential factors model that includes 15 levels ($2^3 + 2 \cdot 3 + 1$).

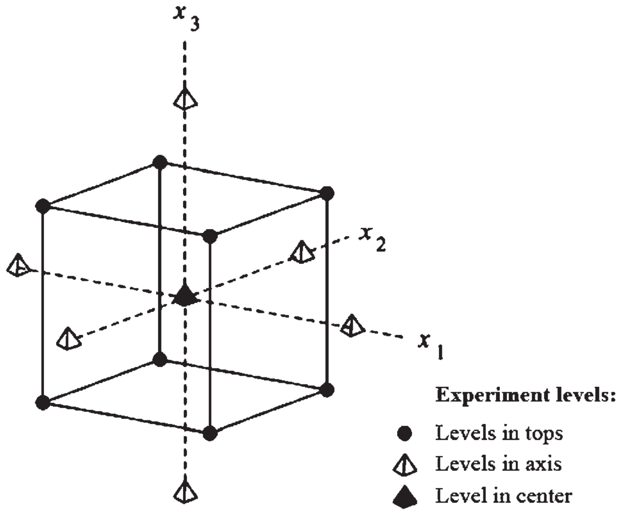

Figure 1 Central composite experiment design with three influential factors [4]
***Slika 1.** Centralno kompozitni plan pokusa sa 3 faktora* [4]

Additional runs in experiment design center are used in order to compare measurable values of dependent variable in the center with arithmetic mean for the rest of experiment [5].

All tests according to experiment scheme design were carried out on new, unused pipe specimens made of axially cut PE 80 pipes with outside pipe diameter *DN* 63 mm, pipe wall thickness *EN* 5,8 mm and *SDR* 11 (Standard Dimensional Ratio, a ratio of *DN* and *EN*). Table 1 shows factors and their levels, including five runs in center, with coded values.

***Table 1** Factors and their levels with five runs in center with coded values* [4]
***Tablica 1.** Faktori i njihove razine uz 5 stanja pokusa u centru s kodiranim vrijednostima* [4]

Std	Factors		
	***A*, mm**	***B*, mm**	***C*, bar**
1	-1	-1	-1
2	-1	-1	1
3	-1	1	-1
4	-1	1	1
5	1	-1	-1
6	1	-1	1
7	1	1	-1
8	1	1	1
9	-1,682	0	0
10	1,682	0	0
11	0	-1,682	0
12	0	1,682	0
13	0	0	-1,682
14	0	0	1,682
15 (C)	0	0	0
16 (C)	0	0	0
17 (C)	0	0	0
18 (C)	0	0	0
19 (C)	0	0	0

Based on experiences in practice, the domain of testing influential factors was defined. Notch length *A* was varied from 16 to 184 mm, notch depth *B* from 1,32 to 4,68 mm, and internal pressure *C* from 1,96 to 12,04 bar and thereby factors and their levels with 5 runs in the center were determined (Table 2) [6].

***Table 2** Factors and their levels with 5 runs in center with real values* [6]
***Tablica 2.** Faktori i njihove razine uz 5 stanja pokusa u centru sa stvarnim vrijednostima* [6]

Std	Factors		
	***A*, mm**	***B*, mm**	***C*, bar**
1	50	2	4
2	50	2	10
3	50	4	4
4	50	4	10
5	150	2	4
6	150	2	10
7	150	4	4
8	150	4	10
9	16	3	7
10	184	3	7
11	100	1,32	7
12	100	4,68	7
13	100	3	1,96
14	100	3	12,04
15 (C)	100	3	7
16 (C)	100	3	7
17 (C)	100	3	7
18 (C)	100	3	7
19 (C)	100	3	7

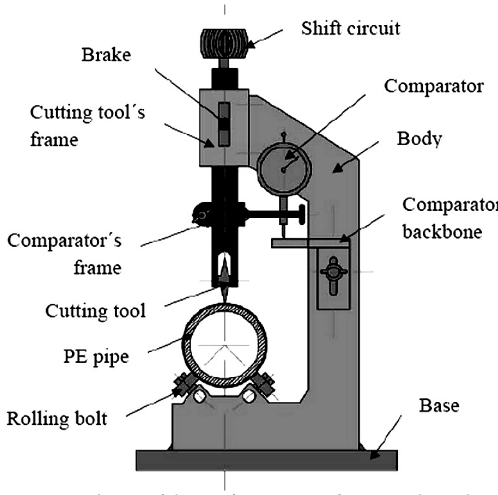

***Figure 2.a** Scheme of device for cutting of an initial axial notch* [6]
***Slika 2.a.** Skica naprave za urezivanje početnog aksijalnog zareza* [6]

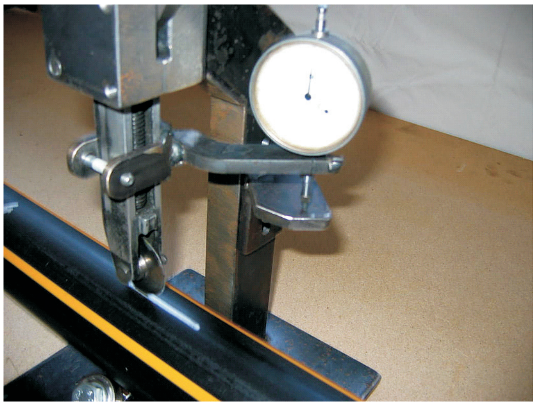

***Figure 2.b** Device for cutting of an initial radial notch* [6]
***Slika 2.b.** Naprava za urezivanje početnog radijalnog zareza* [6]

Figures 2.a and 2.b show the scheme of device and the device made for cutting of an initial axial notch with controlled length and depth on PE 80 pipe specimen.

All pipe specimens were prepared (got their levels - table 2) and tested at 80 °C under conditions defined in HRN EN ISO 9080 standard [7]. Figure 3 shows prepared pipe specimen while mounting into hot water tank at 80 °C.

***Figure 3** Mounting of pipe specimen into hot water tank* [6]
***Slika 3.** Uranjanje ispitnog tijela u toplu vodu* [6]

According to HRN EN ISO 9080 standard, all prior axially cut pipe specimens were submitted to the influence of various internal pressure values at 80 °C until burst at initial notch. Test conditions were set up and controlled on control unit (Figure 4) for testing pipes under pressure according to HRN EN ISO 9080 [6, 7].

***Figure 4** Control unit* [6]
***Slika 4.** Upravljačka jedinica ispitne stanice* [6]

***Figure 5** Pipe bursting at initial notch*
***Slika 5.** Puknuće cijevi na zareznom oštećenju*

Beginning of time measuring was conditioned by achieving given pressure values on control unit. Time was measured until the moment when pressure in pipe started to fall down which was a result of pipe bursting. Pipe bursting time (t_f) was measured and recorded for every experiment design level. Figure 5 shows pipe specimen (made of PE 80 pipes) bursting at initial notch.

2.2 Results and Discussion
Rezultati i rasprava

Table 3 shows results of experiment on PE 80 pipes with axial notches. Due to exceptionally long time of experimental investigation (some levels lasted more than 2,5 years) it was not possible to carry out all levels to the end of investigation (until every pipe burst) which is situation at 13th level (Table 3) [6].

***Table 3** Results of experiment on PE 80 pipes with axial notches* [6]
***Tablica 3.** Rezultati pokusa za cijevi od PE 80 s aksijalnim zarezima* [6]

Pipe NO.	Std	*A*, mm	*B*, mm	*C*, bar	t_f, h
17	1	50	2	4	14066,40
19	2	50	2	10	19,64
12	3	50	4	4	181,21
5	4	50	4	10	0,36
15	5	150	2	4	13323,17
13	6	150	2	10	20,40
11	7	150	4	4	95,88
4	8	150	4	10	0,01
1	9	16	3	7	221,65
2	10	184	3	7	18,84
6	11	100	1,32	7	8608,47
18	12	100	4,68	7	0,01
16	13	100	3	1,96	**11903 ***
7	14	100	3	12,04	0,01
9	15(C)	100	3	7	24,71
14	16(C)	100	3	7	16,52
10	17(C)	100	3	7	32,48
3	18(C)	100	3	7	20,50
8	19(C)	100	3	7	23,11

Mathematical – statistic analysis of experimental data (Table 3) was carried out by using software package Design Expert 7.0.1 [8]. In so doing the value of one data where pipe did not burst (Table 3) was also considered.

Because of specific diffraction of experimental results it was necessary to carry out the so – called power transformation of response function in which the response function was powered by factor 0,2. Therefore, all results, which follow, are displayed as the power of actual values.

Cubic model was chosen for it gives the most suitable regression function compared to linear and quadratic models that were also used for data cultivation. The cubic model assumes the main effects of factors A, B and C, their quadratic terms A^2, B^2 and C^2, first order interactions AB, AC and BC and their cubic terms A^3, B^3 and C^3.

Analysis of variance has shown that some of full cubic model terms are insignificant (their significance is less than 0,05). Therefore, the cubic model was reduced to significant terms and by that, more strength conditions of significance estimation for the rest of the model terms were achieved [6, 8].

Finally, the calculated mathematical model of response function for PE 80 pipes with axial notches at temperature = 80 °C (regression function) is as follows:

$$t_f^{0,2} = 28{,}57132 - 0{,}042348 \cdot A - 11{,}18737 \cdot B - 2{,}12836 \cdot C + 0{,}23705 \cdot B \cdot C + 3{,}71508 \cdot 10^{-4} \cdot A^2 + 2{,}34802 \cdot B^2 + 0{,}059004 \cdot C^2 - 1{,}04582 \cdot 10^{-6} \cdot A^3 - 0{,}20994 \cdot B^3 \qquad (1)$$

From equation (1) can be concluded that positive effect (time prolongation) on bursting time of PE 80 pipes with axial notches, at 80 °C, have first order interaction of notch depth and internal pressure *BC* and quadratic terms of notch length, notch depth and internal pressure (A^2, B^2 and C^2). Negative effects (reducing time) on response function have notch length *A*, notch depth *B*, and internal pipe pressure *C* as well as cubic terms of notch length and notch depth (A^3 and B^3), whereat it is important to notice that the influence of main effects *B* and *C* is significantly greater than the influence of main effect *A*.

Analysis of mean effects has shown that main effects *B* and *C* have negative influence on response function (pipe bursting time), and *BC* interaction has positive influence on response function (t_f). This means that increasing of notch depth and internal pressure decreases pipe bursting time, and increasing of notch depth and internal pressure interaction increases pipe bursting time [6, 8].

Determination coefficient R^2 = 0,9953 shows that the model is generally significant (essentially different from random phenomena), which implies that 99 % of dependent variable (pipe bursting time t_f) variation was explained by the variation of independent variables (notch length *A*, notch depth *B* and pipe internal pressure *C*).

Apart from direct entrance of measured values into equation (1) bursting time of axially cut PE 80 pipes can also be estimated by graphic view of response function t_f. Figures 6.a and 6.b show response surface and contour plot of axially cut PE 80 pipes response function depending on notch depth and internal pipe pressure with constant notch length *A* = 100 mm [6].

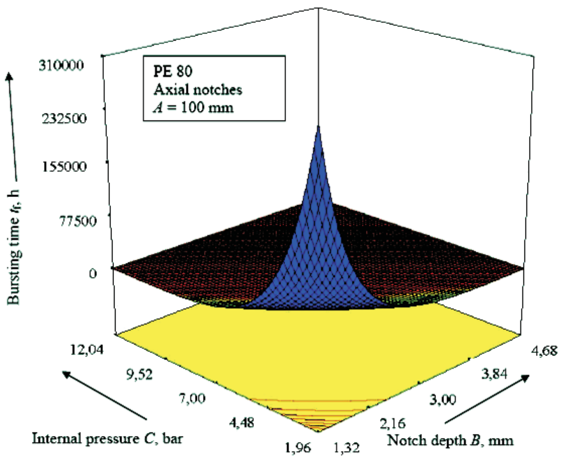

***Figure 6.a** Response surface (PE 80 pipes with axial notches, A = 100 mm)* [6]
***Slika 6.a.** Odzivna površina (cijevi od PE 80 s aksijalnim zarezima, A = 100 mm)* [6]

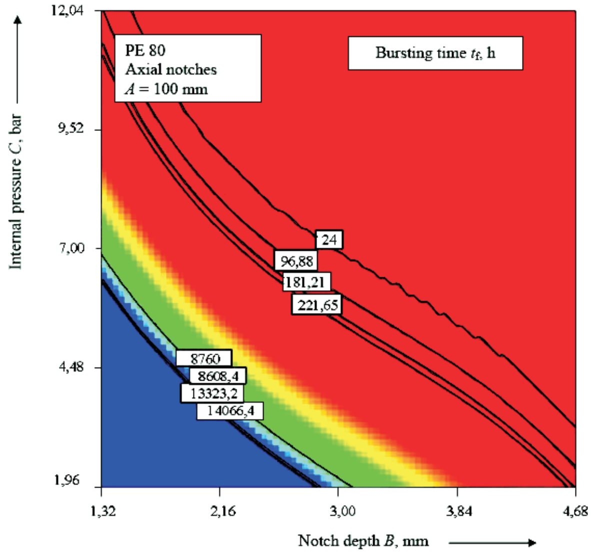

***Figure 6.b** Contour plot (PE 80 pipes with axial notches, A = 100 mm)* [6]
***Slika 6.b.** Konturni dijagram (cijevi od PE 80 s aksijalnim zarezima, A = 100 mm)* [6]

Graphic views of response function, particularly contour plots are of great help to distributors when they currently have to make a decision whether to replace axially cut PE 80 pipe or not.

2.3 Results' Extrapolation and Discussion
Ekstrapolacija rezultata i rasprava

Experimental results are applicable at 80 °C. Since usual working temperature of pipes mounted into the ground is at 5 °C it was necessary to extrapolate obtained results with extrapolation factor according to standard HRN EN ISO 9080 [7]. Response function was extrapolated to 5 °C by multiplying all terms in bursting time functional dependence (t_f for axially cut PE 80 pipes) with the pertaining extrapolation factor [6].

$$t_f^{0,2} = 2857{,}132 - 4{,}2348 \cdot A - 1118{,}737 \cdot B - 212{,}836 \cdot C + 23{,}705 \cdot B \cdot C + 3{,}71508 \cdot 10^{-2} \cdot A^2 + 234{,}802 \cdot B^2 + 5{,}9004 \cdot C^2 - 1{,}04582 \cdot 10^{-4} \cdot A^3 - 20{,}994 \cdot B^3 \qquad (2)$$

As gas pipeline distribution system is most often at 3 bar, graphic view (contour plot) of pipe bursting time functional dependence t_f on notch length *A* and notch depth *B*, at constant working pressure 3 bar and working temperature of pipes mounted into the ground, is very important to gas distributor for a quick and simple estimation. Figure 7 shows the plot of axially cut PE 80 pipes at constant pressure 3 bar and working temperature 5 °C [6].

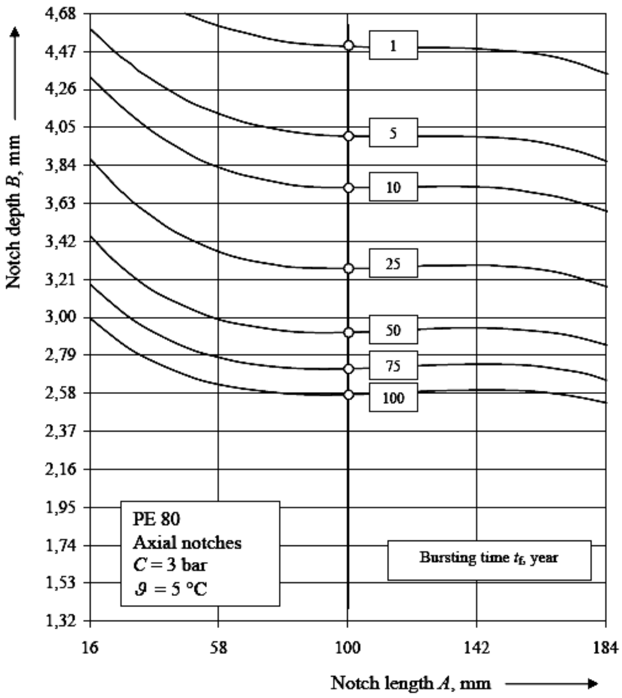

***Figure** 7 Plot (PE 80 pipes with axial notches, C = 3 bar, ϑ= 5 °C)* [6]
***Slika** 7. Dijagram (cijevi od PE 80 s aksijalnim zarezima, C = 3 bar, ϑ= 5 °C)* [6]

3 Conclusion
Zaključak

The results of experimental investigation in this paper carried out on PE 80 pipes (specimens) with axial notches are displayed. According to statistical analysis of experimentally obtained results it may be concluded that notch depth and internal pipe pressure have the strongest negative influence on pipe bursting time while the influence of notch length is also negative, but significantly lesser and can be neglected at the level of significance 0,1.

The approach for pipe bursting time estimation given in this paper is based on practical and easily measured parameters such as notch length, notch depth and pressure in gas pipelines. This approach enables reliable life prediction of axially cut PE 80 pipes and by that provides improved insight into the gas pipeline condition and its maintenance.

It is important to mention that pipes included in experimental investigation have outside diameter *DN* 63 mm and wall thickness *EN* 5,8 mm, therefore it is not possible to apply obtained results on pipes with other dimensions without additional experimental investigations.

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