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ASSESSMENT OF DESTRUCTION CONDITIONS OF THE LONG-TERM OPERATION GAS PIPELINE

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Summary. *For the long-term operation of main oil and gas pipeline steels the method of estimation the critical crack growth resistance J_{Ic} of pipeline steels using experimentally obtained diagram of „force-deflection" specimens destruction was proposed.*

The sizes of through critical cracks $2a_c$ have been calculated and the initial sizes and the shape of the crack-like defects for the investigation of main gas and oil pipelines were evaluated. The obtained data can be a basis for the interpreting of the detected crack-like defects for the technical diagnostics

Key words: *main pipelines, destructive sizes of semi-elliptical crack, through critical crack, critical crack growth resistance, stress intensity critical factor, „force-deflection" diagram.*

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Symbols:

K_{Jc} – *critical crack intensity factor;*
J_{Ic} – *critical crack resistance (critical value J-integral);*
A – *fracture;*
$2a_c$ – *critical sizes of the longitudinal trough crack.*

Statement of the problem. The problem of the main gas pipelines damage being under long – term operation is of special importance nowadays [1, 2]. Losses caused by the seal failure of the main gas pipelines include expenditures to cover gas leak and the cost of the repairing – maintenance operations. The latter can be very sufficient as the main gas pipelines are, as a rule, in the far away areas and it contributes to the recovering terms of damaged units [1, 2]. Besides, accidents are accompanied by the bursts and fires and the pipeline fragments are opened and thrown away in the distance of some hundreds of meters from the place of destruction, which can cause human losses.

It is known, that 75% of gas pipelines of Ukraine were built in the 70 – 80 – ties of the last century. Their technical conditions are critical because of their great defectness and often local damages, resulted in the irreversible changes in the metal structure, caused by the physical – chemical processes, which occur under the influence of the environmental conditions and operation loadings. The process of deformation ageing results in metal embrittlement, which is caused by the microcracks initiation, their further development and merging. Under the influence of the corrosion environment the process of the pipeline metal fracture is caused by the diffusion of atom hydrogen created as the result of electro – chemical reactions into the metal, which is characterised by the decrease of the material strength [3, 4]. This electrolytically created hydrogen, having penetrated into the metal, gets into the microcrak, exchanging the energy with its surface obtaining the molecula structure, which is of greater sizes and less mobility creating the pressure from 10^3 to 10^4 MPa inside the microcrack [5]. It causes the growth of the microcrack and decrease of the internal pressure in it. Further this process is repeated and results in the macrocracks initiation fostering their further development.

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Besides, sufficient mechanism of the damage accumulation in the pipeline steels during their long – term operation is the mechanism, which deals with the dislocation displacement and groupping affected by the operation loadings. It results in the microcracks initiation, their development and merging [6, 7].

Analysis of the available investigations. Analysis of the heavy damages, which arose at the main gas pipelines of Ukraine in 2003 – 2007, has testified, that characteristic cause of such destructions was the initiation of the crack – like defects of 0,45 – 0,65 m length and 6 – 12 mm depth according to the mechanism of corrosion cracking under stress (stress corrosion), caused by the damage of the pipes protective coating, high ground corrosion activity and breaking of the electrochemical protection regimes in the damaged areas of the pipeline [8, 9].

Thus, in April 2003 there happened a fracture of the 1420 mm gas pipeline at the main gas pipeline „Urengoi – Pomary – Uzhorod" (area CS „Stavysche" – CS „Illintsy"). According to the conclusion of the Institute for electric welding named after S.O. Paton the destruction of the main gas pipeline is caused by the corrosion cracking under stress (stress – corrosion) of the pipe metal, which was for the first time since the gas pipelines have been operating in Ukraine. The destruction was caused by the 8 mm depth and 650 mm length crack. More than 80 m of the pipe have been replaced to recover the gas pipeline [8, 9].

Despite the thorough complex investigations carried out at the main gas pipeline „Urengoi – Pomary – Uzhorod" in May, 2007 in the area CS „Stavysche" as a result of the corrosion cracking under stress (stress corrosion) of the pipe metal, there happened a destruction with the pipeline fracture. In this case the reason of the damage was the 6,8 mm depth and 740 mm length crack. The cause of the similar destruction, which occurred in December, 2007 in the area CS „Tllintsy" (Fig. 1) was the 11,8 mm depth and 600 mm length crack [8, 9].

Figure 1. A typical example of a catastrophic destruction of the 1420 mm diameter pipe of the main gas pipeline Urengoy-Pomary-Uzhorod (2007 near the compession station Ilyintsy)

Besides, the effect of the daily fluctuations of the operating pressure in the gas pipelines combined with the operation environment was of special reason, which caused the initiation and the development of the crack – like defects in the pipe walls due to the corrosion fatigue mechanism [10]. Initiation of the fatigue cracks after 15 years of operation of the second line of the main gas pipeline on the 383 km „Krasnodarskiy kray – Serpukhov" in 1999 (1020× 10,5 mm diameter spiral pipes) was caused by the sufficient fluctuation of the operation pressure (from 3,62 till 5,07 MPa) during two monthes [11]. Similar reason of destruction (the marks of fatigue cracks on the destruction surface) was found during the accident at the main gas pipeline „Novopskov – Aksay – Mozdok" in 1996 (1220 ×15,4 mm diameter pipes with the longitudinal seam) after 13 years of operation [11].

Thus, simultaneous effect of static, cyclic and dynamic loadings and the corrosion environment [3, 10, 11] during long – term operation of the main gas pipelines causes the initiation and development of the crack – like defects and corrosion – fatigue cracks, which, being of the critical sizes, result in their destruction [11]. The seasons of accidents at the main gas pipelines as the result of the operation factors (static, cyclic and dynamic loadings as well as the corrosion environment) can be subdivided into [1 – 3, 9 – 11]:

– through local corrosion damages (pits, flaws);

– pipe fractures caused by the initiation and development of the corrosion – fatigue cracks up till critical sizes in both basic metal and in the metal of the pipe weld seam thermal area.

Analysis of the accidents, which arise while the gas pipeline operating, testifies their two possible options [1]. In the first case the seal failure is available, the second is characterised by the pipeline catastrophic (snow – slip) destruction, which is of some dozens meters to some kilometers. The specific conditions of one of these options is the critical size of the through crack-like defect, which depends on many factors (operating pressure, pipe sizes, low temperature of the transported product, availability of the residual stress, thermal and deformation ageing, specific environment, etc.).

That is why determination of the critical sizes of the through crack – like defects and prediction of the uncontrolled fracture conditions of the damaged pipes of the main gas pipelines is the scientific – technological problem of paramount importance.

The Objective of the paper is to estimate the fracture conditions of the main gaspipe of long – term operation, which is based on the approaches of the fracture mechanics.

Statement of the task. The method in question deals with two stages of investigation. At the first stage the critical crack resistance of the investigated pipe steel was found experimentally. The second stage deals with the calculation estimation of the possible catastrophic destruction of the gas pipeline, in which the through crack is available.

It should be noted, that the pipe steels are specified as highly elastic ones [2], that is why for determination of their crack propagation resistance the methods of linear fracture mechanics are not proper.

While estimating the non-damaged pipeline with the through crack it should be taken into account, that the begining of the through crack propagation in the pipe wall must be estimated according to the fracture energy criterion [12]: the crack begins to grow, if the energy intensity J, which was released, is of critical value J_c,

$$J_* = J_c \,. \tag{1}$$

Critical crack strength J_{Ic} was found experimentally according to the method of determination of material crack strength characteristic under bending of rectangular cross – section specimen [13, 14], using experimentally obtained specimens fracture diagram „force – deflection" in the conditions, when the loading force is maximal and the crack growth is found.

To find critical static crack resistance of the pipe steel metal bar specimens with the rectangular cross section of $t = 10\,mm$ thickness, $b = 14\,mm$ height and $l = 150\,mm$ length (Fig. 2) have been used.

1) 2)

Figure 2. General view of the 19G steel specimen (1) with a rectangular cross section (2)

Here the correctness of the J – integral application was specified by the condition

$$b > \frac{25 \cdot J_{1c}}{0,5 \cdot \left(\sigma_{0,2} + \sigma_B\right)}. \qquad (2)$$

The specimens were prepared to the experiment as follows: after mechanical treatment the V-like stress concentrators of 10% depth of the specimen thickness have been spread. After that the specimen has been mounted on the high – frequency cantilever bending installation, with which the initial fatique crack was initiated, the lenglt of which (including the V-like concentrator depth) was of the 40 – 50% specimen thickness [13, 14]. The loadings were chosen so, as they could be in 10 – 15% less than the initial value in the experiment. In the area of the V-like stress concentrator from the side of the tensile stress the deflection feeders was fixed, which structurally consisted of two cantilevers, on which tensorresistors connected by the bridge network have been sticked. The 12B voltage has been supplied to one of the bridge diagonal, from the other the signal was taken, which was changed propotionally to the specimen deflection. The bridge was supplied by the DC supply unit VIP-09, and the deformation diagram was recorded by the PDA1-01self-recorder.

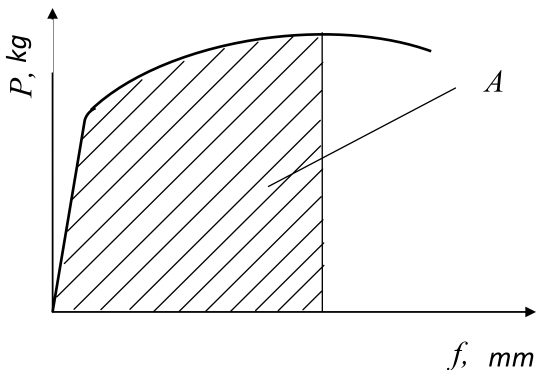


Figure 3. Diagram of P-f deformation

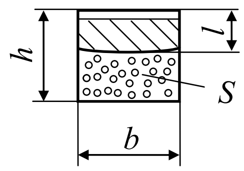


Figure 4. Determination of the area of the deformed specimen S

The testing was carried out on the versatile tensile – testing machine FP-100/1. The speed of the specimen loading was 1 mm/min and was constant during all period of testing.

The experiment began with the measuring of the sizes of the operating cross – section of the specimen and the distances between the supports ($L = 4,5 \cdot h$). The specimen was mounted on the loading device and the deflection feeders were fixed. Having balanced the measuring instruments, the specimen was loaded up till it losts its carrying properties simultamously recording the fracture diagram (Fig. 3). After the experiment the measuring of the deformation (fracture) surface wrecking of the specimen was taken and its area S was determined (Fig. 4) according to the equation

$$S = \left(h - l^*\right) \cdot b. \qquad (3)$$

According to the obtained experimental data the fracture work was determined (dashed area of the diagram in Fig. 2)

$$A = \int_0^{f_{max}} P(f)\, df \ . \tag{4}$$

The value J_{Ic} was determined as the work A spent for the cracked specimen deformation as the construction component, under which it looses its carrying properties treated as the net area of the deformed specimen surface S (Fig. 5).

$$J_c = \frac{A}{S} .$$

Besides, while finding the critical stress intensity factors K_{Jc}, it was taken into account, that its dimension is $\text{MPa} \cdot \sqrt{\text{m}}$. As the dimensions of the structural elements are presented in millimeters for calculating K_{Jc} the obtained result was multiplied by $\sqrt{10^{-3}}$.

The characteristics of the critical crack resistance were presented by the critical stress intensity factor K_{JC}, which was found according to the equation [2], in which the condition of small – scale yield under the plane deformation have been obtained.

$$K_{Jc} = \sqrt{\frac{J_c \cdot E}{\left(1-\mu^2\right)}} , \tag{5}$$

where J_{Ic} – critical crack resistance;

E – the Young's modulus ($E = 10^{11}\ Pa$);

μ – the Poisson's ratio (for the low alloyed steels $\mu = 0{,}3$).

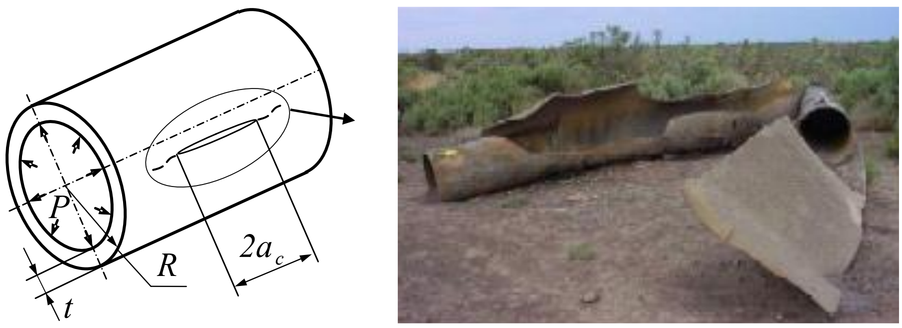
The calculation estimation of the possible catastrophic destruction of the gas pipeline pipe with the through crack was carried out taking advantage of the proposed criterion [15, 16], according to which the critical sizes $2a_c$ of the longitudinal through crack can be found (Fig. 5, 1):

$$a_c = \frac{1}{\pi} \cdot \left(\frac{K_{Jc}}{F_I \cdot \sigma_p} \right)^2 , \tag{6}$$

where σ_p – maximum tensile stresses, $\sigma_p = \frac{P_{max} R}{t}$, $\lambda = \frac{a_{K_I}}{\sqrt{R \cdot t}}$;

a_{K_I} – through crack semi – length;

$$F_I = 1 + 0{,}072449 \cdot \lambda + 0{,}64856 \cdot \lambda^2 - 0{,}2327 \cdot \lambda^3 + 0{,}038154 \cdot \lambda^4 - 0{,}0023478 \cdot \lambda^5 .$$



1) 2)

Figure 5. Schematic representation of the through corrosion-fatigue crack (1) in the pipe wall and the consequences of gas pipeline accidents caused by its longitudinal development (2)

Under the condition, when the through crack size is equal or greater than the critical size $2a_c$ of the longitudinal through crack, there arise accidents [1, 2, 8], when the crack coming out to pipe surface propagates along its axis causing its further fracture (Fig. 5, 2).

Non – damaged gas pipeline with the through crack (Fig. 5, 1) will be provided under the condition, when the size of the through defect is less than the critical size $2a_c$ of the longitudinal through crack. In this case [17] formation of the flow is possible – the through hole, under which the conditions for the catastrophic fracture of the gas pipeline pipe are not available, the gas leakage being possible.

The result of investigations. The fragment of the main gas pipeline „Shebelynka – Poltava – Kyiv“, (720×14) being in operation for 41 years, has been the investigation material. Chemical composition of the investigated steel is presented on Table 1.

Table 1

Chemical composition of the investigated steel 19G, mas. %

C	*Mn*	*Si*	*V*	*Cu*	*Al*	*Ni*	S_{max}	P_{max}	*Fe*
0,19	1,52	0,32	0,09	0,13	0,04	0,09	0,018	0,016	the rest

The mechanical properties of the long-term operated pipe steel [Table 2] were determined due to the conventional procedure [18] of the tensile testing of the quintuple cylinder specimens.

Table 2

Mechanical properties of 19G steel

σ_B, *MPa*	$\sigma_{0,2}$, *MPa*	δ, %	ψ, %
481,5	328,0	22,7	57,3

Estimation of conditions, under which the fracture of the gaspipe pipe metal occurs, has been carried out due to the method [13, 14], finding the value J_c experimentally. With this purpose five $150{,}0 \times 10{,}0 \times 14{,}0$ mm specimens were cut out from the main gas pipeline pipe coil (Fig. 2).

Here the work A (area under the deformation diagram, Fig. 5) was determined, which was spent on the deformation of the specimen with the preliminary formed crack $l_{cep} = 0{,}45 \cdot h$ as the component of the structure, under which it losses its carrying properties, related to the net area of the deformed specimen surface S_J (Fig. 4).

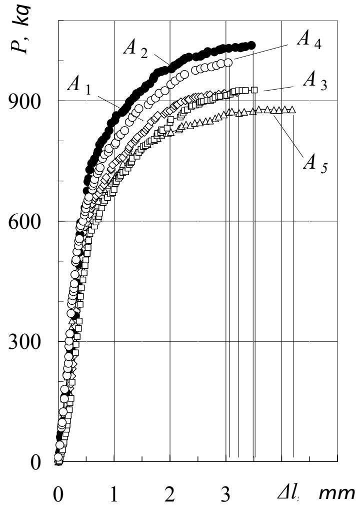


Figure 6. Diagram of deformation of specimens from the fragment of gas pipeline pipe

The characteristics of the critical crack – resistance (Table 3) in the paper are presented by the critical stress intensity factor K_{Jc}, which was found according to the equation (5).

Table 3

Values of critical stress intensity factors K_{Jc}

Specimen	K_{Jc}, $MPa\sqrt{m}$	K_{Jc}^{cep}, $MPa\sqrt{m}$
1	263,45	282,91
2	294,60	
3	279,37	
4	267,03	
5	310,09	

Using the equation (6) the values of critical sizes $2a_c$ of the longitudinal through crack ($2a_c = 344\ mm$) for the pipe of the main gas pipeline „Shebelynka – Poltava – Kyiv", which is in the air environment, have been found.

The analysis of the investigation results for the pipe steel 17Г1С presented in the paper [19] testifies, that the effect of the ground water causes the decrease of the critical sizes of the longitudinal through crack in about 15%.

Thus, the through defects of more than 300 mm length are potentially dangerous as they can cause catastrophic destruction of the gas pipeline under real operation conditions.

Conclusions. The method of estimation the conditions for the catastrophic destruction of the long – term operating gas pipeline, has been proposed. Basing on the experimentally obtained diagrams of the specimen fracture „force – deflection" it makes possible to take into account the processes of ageing and degradation in the long – term operated pipeline steels and to calculate the critical sizes of the through crack ($2a_c$) according to the crack – resistance criterion.

The obtained numerical data can be used as the basis for the interpreting of the crack – like defects found in the process of the technological diagnostics of the long – term operated gas pipelines.

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ОЦІНКА УМОВ РУЙНУВАННЯ ГАЗОПРОВОДУ ТРИВАЛОЇ ЕКСПЛУАТАЦІЇ

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Резюме. *Для тривало експлуатованої сталі магістрального газопроводу «Шебелинка – Полтава – Київ» визначено критичну тріщиностійкость* J_{Ic} *трубопровідної сталі 19Г на основі експериментально отриманих діаграм руйнування зразків «зусилля – прогин». За критерієм тріщиностійкості обчислено розміри наскрізних критичних тріщин* $2a_c$*. Отримані дані можуть слугувати базою для інтерпретації виявлених у процесі технічного діагностування тріщиноподібних дефектів.*

Ключові слова: *магістральні газопроводи, наскрізна критична тріщина, критична тріщиностійкість, критичний коефіцієнт інтенсивності напружень, діаграма «зусилля – прогин».*

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