Structural Integrity Assessment of Heat-and-Power-Engineering Pipelines with Corrosion Defects

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Abstract. Problem of corrosion and corrosion fatigue damaging of feeding pipelines of heat-and-power generating units under long-term operating conditions is considered. The two main factors were taken into account: degradation of metals properties and purity of operating aqueous environment that causes by ecological pollution of natural water scoop. Corrosion fracture mechanics approach for assessment of workability and fracture risk of pipelines with crack-like defects is proposed, which based on conception of threshold and critical cracks depth and also corrosion fatigue crack growth parameters.

Introduction

In general, reliability and safety of heat-and-power engineering equipment is actual problem for Ukraine as well as other industrial countries [1, 2], because for prevails number of heat power plants the planned life of exploitation will be expired at nearest future [1]. As typical example, the statistic data on exploitation history of two Ukrainian power plants is given in Table 1. Further extension of their work requires the detailed inspection and expert conclusions for all critical components of heat-and-power generating units and also revision of their operating regimes.

From this point of view, the feeding pipelines are critical structures, which have the length of several hundred meters for each heat-and-power generating unit and different dimension-types of tubes: external diameter exceeds 500mm and maximal wall thickness is about 50mm.

From engineering practice [1] it has been shown that service life extension of such structures should be based on taking into account of two main factors: degradation of metals properties and aging pipelines components that causes by long-term exploitation and purity of operating aqueous environment that causes by ecological pollution of natural water scoop.

The joint action of these factors leads to accelerated corrosion and corrosion fatigue damaging of pipelines components [3, 4]. Under early stage of damaging the corrosion factor is dominated (Fig. 1). This process can be classified as sequence: general corrosion of surface - initiating of localised corrosion - corrosion furrows and corrosion pits nucleation.

These corrosion defects serve as effective stress concentrators and during exploitation time the some number of corrosion defects is transformed into corrosion fatigue cracks. Depending on combination of corrosion/fatigue factors these cracks can be sharp or blunted by corrosion and also branched [1]. Thus, exploited pipeline contains simultaneously the different types of defects and such structural element should be assessed from position of its workability and potential risk of failure.

For solution of this problem the corrosion fracture mechanics methods are applicable together with the special laboratory tests of metal from pipelines, which were exploited under assigned operating conditions [5].

Table 1 Statistic data on the exploitation regimes of power plant units [1].

Heat-and-power generating units	Time of exploitation in thousand hours	Number of start-and-stop	Number of loading cycles
Power plant V	120-150	170-350	850-1750
Power plant L	135-145	360-455	1800-2275


(a) (b) (c)

Fig. 1 Corrosion damaging of feeding pipelines of heat-and-power-generating units under operating conditions: general corrosion of surface (a), initiating of localised corrosion (b), corrosion furrows and corrosion pits nucleation (c).

Fracture Mechanics Approach for Assessment of Workability and Fracture Risk of Pipelines with Crack-Like Defects

Crack-like defects modelling. The most characteristic types of corrosion and crack-like defects were considered, which detected by non-destructive methods and visual observation of exploited tubes, namely: corrosion furrow, corrosion pit and corrosion fatigue crack [1, 2]. All types of defects were modelled [6, 7] by semi-elliptical cracks (Fig. 2) with different ratio of their half-axis a and c: $(c/a) = 0{,}01 - 0{,}8$.

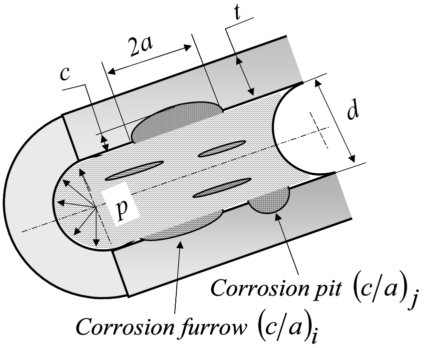

Fig. 2 Model presentation of corrosion and corrosion fatigue defects in pipelines wall.

Stress intensity factor for tube with semi-elliptical crack under internal pressure. For calculation a stress intensity factor for longitudinal semi-elliptical crack in tube wall under internal pressure p (Fig. 3), the following expression was used [5, 6]:

$$\Delta K_I = \Delta\sigma\cdot\sqrt{\pi c}\cdot\left\{\frac{1}{\sqrt{\pi}}\cdot\frac{1.12-0.48\beta+0.13\left(\frac{2\theta}{\pi}\right)^2\cdot\beta(3\beta-2-\alpha)}{1-\alpha(1-0.75\beta)}+\right. \\ \left.+\frac{1.13}{k_f}\left[\beta\left(\frac{2\theta}{\pi}\right)^2\cdot(\alpha-0.4+0.6\beta)+\beta(1-1.4\alpha)+0.62\lambda(1-\beta)\cdot\psi(\alpha)\right]\right\}; \qquad (1)$$

where $\Delta\sigma$ is a tensile stress range per loading cycle: $\Delta\sigma=(\Delta p\cdot d)/2t$; Δp is pulsation of a pressure p in pipeline; d is an internal diameter of tube; t is a thickness of tube wall; c is a depth of crack $\beta=c/a$ under $(0\le\beta\le 1)$; a is a crack half length; $\alpha=c/t$; θ is an angle from small axis of semi-elliptical crack; k_f is a coefficient, which takes into account the tube cross section form:

$$\lambda=\begin{cases}1, \alpha\ge 1/20\\ 1.15-60(\alpha)^2;\ 0\le\alpha\le 1/20\end{cases} \qquad \psi(\alpha)=(\alpha)^{-1/2}\cdot\sqrt{(1-\alpha)^{-3}-(1-\alpha)^3}$$

Corrosion fatigue cracks growth resistance. For corrosion fatigue cracks growth behaviour it was assumed that propagating crack saves its semi-elliptical shape, but the ratio of half-axis (c/a) is variable value [8, 9]:

$$c/a=f(C_m,N); \qquad (2)$$

where C_m are the constants, which depend on "material- environment" system; N is number of loading cycles.

Here was also supposed that crack growth rate diagrams [5] fully define of resistance of defects to propagation in pipelines wall in direction of both axis c and a. They have been presented analytically using well-known Paris equation:

$$dc/dN=da/dN=C(\Delta K)^n; \qquad (3)$$

where C and n are the constants of "material- environment" system.

These diagrams are located between two characteristic values of stress intensity factor range ΔK_I, namely [5]: ΔK_{th} - threshold stress intensity factor range and ΔK_{fc} - cyclic fracture toughness. The parameter ΔK_{th} defines of limit load, below which the detected defects can be considered as non-propagated and cyclic fracture toughness ΔK_{fc} indicates the critical loading level, above which the detected defects are potentially able to catastrophic (spontaneous) growth.

The mentioned above parameters were chosen as base for further development of expert assessment of workability and fracture risk of the feeding pipelines with crack-like defects. Here needed data were received with using the special experimental technique [5] and with taken into account both the real metal state of exploited pipelines and actual composition of operating aqueous environment.

Threshold defects depth c_{th} criterion. This criterion is based on relationship between the depth of semi-elliptical crack in tube wall and value of threshold stress intensity factor ΔK_{th} [5, 9]. Here the threshold defect depth c_{th} defines as the semi-elliptical crack depth of given shape (c/a), for which at point $\theta=0$ stress intensity factor is equal of the threshold value: $K_I=K_{th}$. Thus the criterion of the "safe" crack-like defects will be condition [9]:

$$c \le c_{th}(\Delta K_{th}) \text{ under } (c/a) = const. \tag{4}$$

Therefore, all detected crack-like defects in the pipelines by depth $c \le c_{th}$ can be accepted as "safe", inasmuch as they don't have the potential ability to further development in wall depth.

Criterion of limitation of corrosion fatigue crack growth rate. This criterion can be applicable for cases when the detected cracks in pipeline wall slightly exceed the threshold depth: $c > c_{th}$. Here, the assessment of the admissible crack depths in pipeline walls may be realised on the base of limitation of corrosion fatigue crack growth rate [6, 7], i.e.:

$$dc/dN \le (dc/dN)_* . \tag{5}$$

where $(dc/dN)_*$ is the maximum crack growth rate that may be admitted in the wall of pipeline during planned service term between two inspections.

The admissible crack depth c_* in the given pipeline under assigned operating conditions, can be determined as

$$c_* = \Phi(c/a) \quad under \quad (dc/dN)_* = const. \tag{6}$$

For any considered cases the calculation (Eq. 6) may be done with using Eq. 3 for determining of the value $K_I = K_*$, which correspond $dc/dN = (dc/dN)_*$ and then on the basis Eq. 1 the parameter c_* may be found as $c_* = F(K_*)$.

Critical defects depth c_{fc} *criterion*. In this case the assessment is realised according to well-known criterion of brittle fracture mechanics [1, 5]:

$$\Delta K_I \le \Delta K_{fc} ; \tag{7}$$

where ΔK_{fc} is a cyclic fracture toughness [5].

On this ground, the critical defect depth c_{fc} defines as the semi-elliptical crack depth of given shape (c/a), for which at point $\theta = 0$ stress intensity factor is equal of the critical value: $K_I = K_{fc}$ and the criterion of the "critical" crack-like defects will be condition:

$$c \le c_{fc}(\Delta K_{fc}) \text{ under } (c/a) = const. \tag{8}$$

Thus, all detected crack-like defects in the pipelines by depth about $c \approx c_{fc}$ can be considered as critically dangerous, because exist high probability to their spontaneous growth that will lead to catastrophic failure of pipeline.

Diagram for assessment of structural integrity of pipeline with crack-like defects. Grounding on considered above criteria, the diagram [9] for assessment of workability and fracture risk of pipeline of the given dimension-type with crack-like defects of different shape can be built (Fig. 3).

This diagram consists of three zones. The area below curve $c_{th} = F_1(c/a)$ determines the conditions of safe exploitation and area above curve $c_{fc} = F_3(c/a)$ indicates of brittle fracture zone. The area between curves $c_{th} = F_1(c/a)$ and $c_{fc} = F_3(c/a)$ is zone of subcritical crack-like defects growth. Here, for assigned operating conditions of pipeline, the appropriate limiting curve $c_* = F_2(c/a)$ may be built. Below this curve growth rate of all existed defects will not exceed the admitted maximum rate during planned operation term to next inspection of pipeline.

Thus, all detected defects by NDT methods under inspection can be compared with described above diagram and expert assessment of workability and fracture risk of the given pipeline can be done.

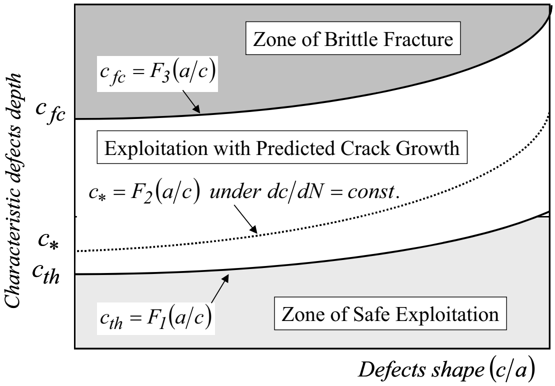

Fig. 3 Schematic view of diagram for assessment of structural integrity of pipeline with crack-like defects.

Determination of Corrosion Fatigue Crack Growth Resistance of Feeding Pipelines Metal

Experimental procedure. The power engineering steel 16HS ($\sigma_Y = 250 MPa$ and $\sigma_U = 480 MPa$) was investigated. Steel chemical composition (in weight %): C=0.12-0.18; Si=0.4-0.7; Mn=0.9-1.2; Cr<0.3; Ni<0.3; Cu<0.3; S<0.04; P<0.03; As<0.08; remainder Fe. The standard beam specimens by thickness of 10 mm and with V-shape notches were machined from metal of tubes. Three different materials were used: metal from new pipe (new metal), metal from pipe-lines of Power plant "V" (metal "V") and metal from pipe-lines of Power plant "L" (metal "L").

Two types of the environments were used [6]. First - an environment of nominal composition (NC) according to rules of power plants exploitation. It was the high purity water under $pH = 7 \pm 0.5$ and conductivity $\chi \leq 3 mS/m$. Second - the same environment but with organic additions (NC+OA): the formic acid (C=3000 μ g/kg) and 2,4-dinitrophenyl (C=400 μ g/kg). It should be noted that these additions were chosen on the base of the preliminary investigations. These electrochemical studies showed that formic acid and 2,4-dinitrophenyl are the most corrosion aggressive additions with respect to pipes metal among others, which were detected in natural reservoir for the given power plants [1, 8].

Corrosion fatigue crack growth tests were carried out under frequency of cyclic loading $f = 1.0 Hz$ and stress ratio $R = 0.7$ that imitates the real pulsation of operating pressure in feeding pipelines of heat-and power generating units. The tests were carried out with using the specially developed technique [5], where the constant environment composition in the crack tip area was provided by circulation of the environment through crack cavity.

Corrosion fatigue cracks growth resistance diagrams of feeding pipelines metal. The corresponding series of the corrosion fatigue crack growth tests were conducted both for different metals and environment composition. The received experimental data were initially presented as scatter plots of crack growth rate versus stress intensity factor range, from which the following basic parameters were determined, namely: constants C and n in Eq. 3; threshold intensity factor range ΔK_{th} and critical intensity factor range ΔK_{fc} (Table 2).

Table 2. Corrosion fatigue cracks growth resistance data for metal of feeding pipelines.

Material – Environment”	n	C, $[\frac{mm/cycle}{\left(MPa\cdot\sqrt{m}\right)^n}]$	$K_{th}, [MPa\cdot\sqrt{m}]$	$K_{fc}, [MPa\cdot\sqrt{m}]$
New metal – NC	11.21	$8.71\cdot10^{-16}$	6.32	22.05
New metal – NC+OA	10.55	$3.02\cdot10^{-15}$	6.36	23.79
Metal “L” – NC	32.87	$1.66\cdot10^{-33}$	6.83	9.94
Metal “L” – NC+OA	18.36	$4.36\cdot10^{-22}$	6.86	14.57
Metal “V” – NC	14.07	$1.66\cdot10^{-18}$	6.89	18.35
Metal “V” – NC+OA	10.66	$3.24\cdot10^{-15}$	6.11	22.87

The main observation to be made from these results is decreasing of the corrosion fatigue crack growth resistance characteristics of exploited metal with comparison to new that shows on degradation of materials properties under given operating conditions. Especially it can be seen for metal from Power plant L, for which crack growth rate curve have the highest steep slope. It is inauspicious for providing of the pipelines workability, because any negligible operating overload may lead to significant increasing of corrosion fatigue crack growth rate [5, 7].

These data were used for forecasting of structural integrity and fracture risk of feeding pipelines of different dimension-types with crack-like defects.

Assessment of Structural Integrity and Fracture Risk of Feeding Pipelines with Crack-Like Defects from Different Power Plants

Tubes size and operating conditions. The four dimension-types of tubes ($D\times t$, $[mm]$) are used, namely: 526×50, 467×45, 405×40 and 165×16. High purity water at maximal pressure $p_{\max}=35MPa$ served as nominal operating environment. The possible operating pulsation of pressure was $\Delta p=10.5MPa$.

Influence of exploitation term. Based on proposed fracture mechanics approach and corrosion fatigue crack growth resistance data, the diagrams of structural integrity and fracture risk assessment for feeding pipelines with crack-like defects have been built both for different operating conditions and dimension-types of pipes.

The diagrams, which are shown in Fig. 4, demonstrate the influence of exploitation term. It can be seen that degraded metal from Power plant L possesses the very low corrosion fatigue crack growth resistance and as result the characteristic crack depths c_{th}, c_* and c_{fc} are very low than for new pipes. Besides that, a difference between curves $c_{th}(c/a)$ and $c_{fc}(c/a)$ is significantly smaller for exploited pipes than new one.

These facts show on the low reliability of exploited pipes where even relatively small defects have potential ability to propagation and difference between threshold and critical crack depth is only few millimetres.

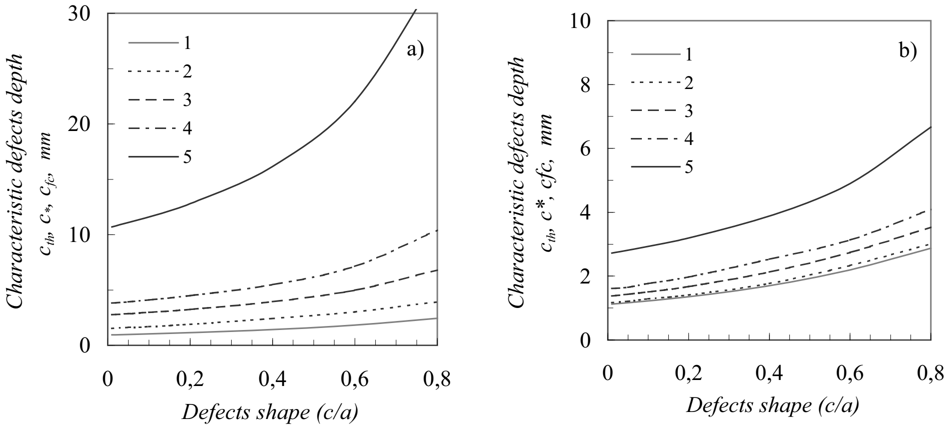

Fig. 4 Diagrams of structural integrity assessment for new (a) and exploited on Power plant L: (b) pipes with crack-like defects for nominal environment: 1 - c_{th}; 2 - $c_*\left(dc/dN = 10^{-5}\ mm/cycle\right)$; 3 - $c_*\left(dc/dN = 10^{-4}\ mm/cycle\right)$; 4 - $c_*\left(dc/dN = 10^{-3}\ mm/cycle\right)$; 5 - c_{fc} (pipes size: D=526 mm; t=50 mm).

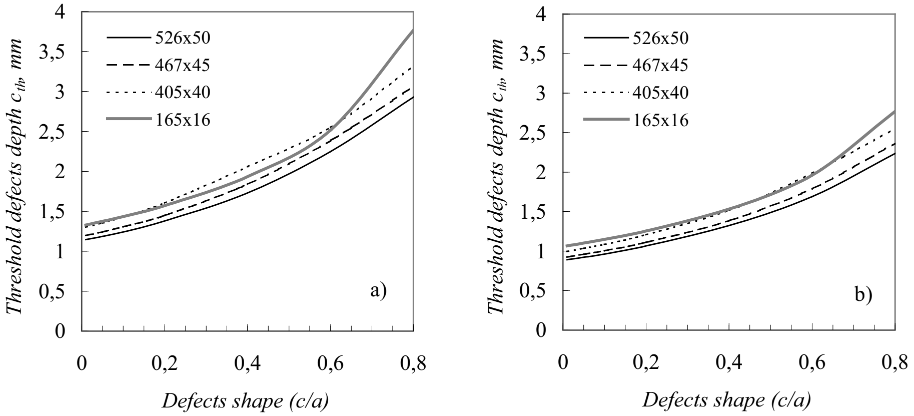

Fig. 5 Threshold defects depth c_{th} versus defects shape c/a for different size of pipes from Power plant V: a - operating environment of nominal composition, b - with organic admixtures.

Influence of environmental composition and pipes size. The factor of operating environment is important for the given considerations, because it defines the corrosion fatigue crack growth behaviour in pipelines wall. This statement is confirmed by results, which are shown in Fig. 5. The presence of organic admixtures in operating environment increases the risk of failure, because in this case the threshold defects depths c_{th} are decreasing. Finally it should be noted that actual size of threshold and critical defects depths are depended on the given pipe size, that is clear from the analysis of the structure of relations Eq. 1, 4 and 8.

Summary

Problem of corrosion and corrosion fatigue damaging of feeding pipelines of heat-and-power generating units under long-term operating conditions was considered with taken into account of metal degradation and real composition purity of operating aqueous environment.

Corrosion fracture mechanics approach for assessment of workability and fracture risk of pipelines with crack-like defects is proposed, which based on conception of threshold and critical cracks depth and also corrosion fatigue crack growth parameters.

For assessment of structural integrity, the special diagrams are developed, which contain three zones: safe exploitation, brittle fracture risk and zone of exploitation with predicted growth of existed defects. Here, the importance of factors of exploitation term, location and shape of defects and composition of operating environment has been shown.

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