Durability Assessment of Welded Dissimilar Pipes with Corrosion Defects Based on Different Failure Criteria

Orest BILYY

5, Naukova Str., Karpenko Physico-Mechanical Institute of the NAS of Ukraine, Ukraine

borest@ipm.lviv.ua

Keywords: welded dissimilar pipe, corrosion defect, maximum stress, stress intensity factor, failure criterion.

Abstract. Failure assessment procedures for pressurised components play a key role in safe operation of piping systems for heat-and-power-engineering. This work contains an analysis of corrosion damaging of welded dissimilar pipes under operating conditions and also proposes some approaches for expert conclusions of their durability in case of presence of the growing corrosion defects.

The combined welded joints of the pipes of 12X1MΦ low-alloyed pearlitic steel and X18H10T stainless austenitic steel were considered under internal pressure of high purity water ($p = 140$ bars). Here, the objects of study were welded pipes with external diameter $d = 42$ mm and wall thickness $t = 4$ mm in the delivery state and after operation during 185 000 hours at the heat power plant. Based on analysis of in-service failures, the internal circumferential corrosion defects at the welded zone were studied. Four possible cases of defect location were considered, namely: in 12X1MΦ steel; in welding zone neighbouring with this steel; in welding zone neighbouring with X18H10T steel and in X18H10T steel.

It has been assumed that corrosion defect growth realises by mechanism of local electrochemical dissolution of metal. For calculation of defect depth as function of time the numerical-analytic model of dissimilar welded joint as three-electrode electrochemical system was used. We developed this model earlier with using of the fundamental electrochemical parameters of composing materials, which can be received by standard potentiometric methods.

The calculated diagrams “defect depth – time” served as basis for structural integrity and durability assessment of the given components. Two possible cases were considered: first – defect as notch with finite radius, and second – defect as crack. For notch the maximum stress criterion was applied, i.e.: $\sigma_{\max} \le \sigma_{YS}$, where $\sigma_{\max}$ is maximum stress at notch tip; σ_{YS} is yield stress of composing materials. For the case of crack the brittle fracture criterion was used: $K_I \le K_{IC}$, where K_I current value of stress intensity factor at crack tip and K_{IC} – its critical value (fracture toughness of given composing material). The durability of each component of welded dissimilar pipe with growing corrosion defect was determined as the time for achieving conditions: $\sigma_{\max} = \sigma_{YS}$ and/or $K_I = K_{IC}$. Obviously that total durability of given welded joint was defined by the durability of the most weak component.

Introduction

The various corrosion and corrosion-mechanical damages of pipes of elements of water-steam circuit substantially influence on its terms of safe exploitation. For today more than half of failures on the heat-and-power equipment is predefined by an origin and development of the unpredictable local corrosion defects [1, 2]. Among them it is possible to mark out the problem of welded joint damaging. The combined circumferential welded joints of pipe at the superheater end point are considered in this work [1]. It is important to develop the methods for estimation of kinetics of development of localised corrosion damages for their research. Also it should be noted that the problem of circumferential and other defects on the internal surfaces of pipelines research is underrepresented [3, 4].

Object of study

The combined welded joints of pipes of low-alloyed ferrite-pearlitic steel 12X1MΦ and austenitic stainless steel 12X18H10T were studied (Fig. 1a, b). Joints with dimensions of $\varnothing 42\times 4$ mm (internal radius is 17 mm) in the virgin state and after 185 000 hours of exploitation on the heat-power-plants under temperature of 540°C and pressure of 14 MPa were studied. The aim of the research was to obtain the potentiodynamic polarisation curves and to determinate on their ground the base electrochemical parameters, from which it is possible to judge about electrochemical behaviour of the welded joint in the working environments [5].

As a result of the experiments from the potentiodynamic polarisation curves were obtained the base electrochemical parameters, namely: corrosion potentials (from Taffel lines crossing) and cathodic and anodic specific polarisation resistances (φ V, b_k Ω×m^2, b_a Ω×m^2), also the conductivity of the environment ($\kappa = 0.557$ μSm/cm) was determined. These values were obtained from experimental researches for initial impurity content $C_{NaCl} = 0.3\,\%$. The basic electrochemical parameters of the welded joint materials are used from work (see [6]).

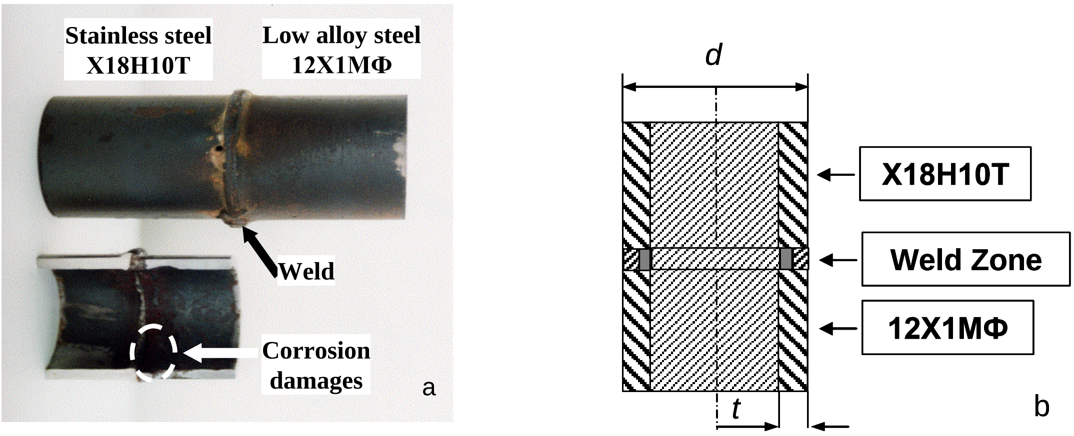


Fig. 1. Object of study (*a*), its schematic presentation (*b*).

Calculation of maximal depth of defects

The next stage of work was the development of the analytical method for determining the corrosion current density on internal surface of dissimilar pipe welded joints. Here each material can be characterised by two parameters, namely: potential of corrosion (φ) and polarisation resistance (b). Using this model of welded joint, the following analytical function for calculation of corrosion current density was derived [6]:

$$i_j = F\left(b_a^j, b_k^j, \varphi_j, \kappa, r_0, l\right); \qquad (1)$$

where: i - corrosion current density on internal surface of welded pipes; $j = 1\ldots3$ – number of the component of the welded joint; l – distance from the centre of welded zone to one of the base materials

This function served as basis for calculation of the distribution of corrosion current density on internal surface of welded pipes under different conditions of exploitation. Here, the special analytic method for “sewing” the solutions was proposed and numerical procedure of calculation was developed [6].

Comparison of the values of corrosion current density for the case of initial state and after some exploitation time reflects on increasing of corrosion activity of exploited welded joint that reflects its degradation as result of long-term exploitation.

According to the aforesaid with taken into account statement that corrosion current density defines the rate of electrochemical dissolution of metal, the method for assessment of localised corrosion damaging in dissimilar pipe welded joints was proposed:

Describing in the first approximation the time-history of electrochemical parameters b and φ by the linear law and using the function (1) it is possible to calculate the depth of damage h of components of the investigated joint during the set time of exploitation T. On the base of this calculation [6] there were obtained the diagrams "depth of defect - time" according to the equation:

$$h = \frac{326.8}{D} \cdot \frac{j_i\left(b_a^i, b_k^i, \varphi_i, \kappa, l\right)}{\sum_{p=1}^{P} \frac{d_p \cdot \Theta_p}{A_p}}; \qquad (2)$$

where p is a component number; d_p - its relative content by mass; A_p - mass of component atom in atomic units of mass; Θ - valence of the metal; P – number of components; D – density of the alloy; h – depth of corrosion damages.

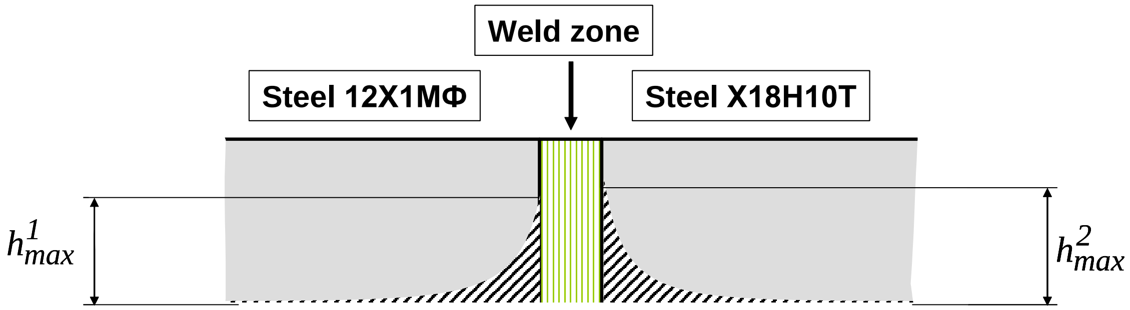


Fig. 2. Schematic presentation of corrosion damages in the walls of the dissimilar pipe welded joint.

The diagrams “depth of corrosion – time” were built basing on such correlation. The final equation (2) defines the “depth of corrosion” in mm per year. Schematically those kinds of diagrams are shown on Fig. 2. According to the proposed scheme the largest corrosion damaging take place on the welded materials in the areas close to welded zone and on the welded zone in the areas close to welded materials. At the same time it can be assert [5] that damages in the areas close to the welded zone are essentially largest then in the welded zone. In this specific case (conductivity of environment $\kappa = 0.557$ μSm/cm; and initial impurity content $C_{NaCl} = 0.3\,\%$) the damage of only the component of joint near the welded zone is observed. While the welded zone itself is not damaging. Though in work [5] the other cases are considered. As a result of this further we will consider the depth of damage in the base materials: 12X18H10T steel and 12X1MΦ steel.

Having the distribution in time of damages depth in the investigated object on the base of function (2) the dependences of maximum depth of damages from exploitation time were presented (Fig. 3 a): ($h^1_{\max}$ – for low alloyed steel; $h^2_{\max}$ – for stainless steel). That kind of dependences served as a base for further modeling of character and geometry of damage for further assessment of strength and lifetime of welded joint components and also welded joint integrally.

The diagrams “Maximum depth of defect – time” (Fig. 3 a) on the base of calculation according to the function (2) were obtained. These diagrams served as base for the assessment of strength and durability of dissimilar pipes components that fits to the welded zone from both sides.

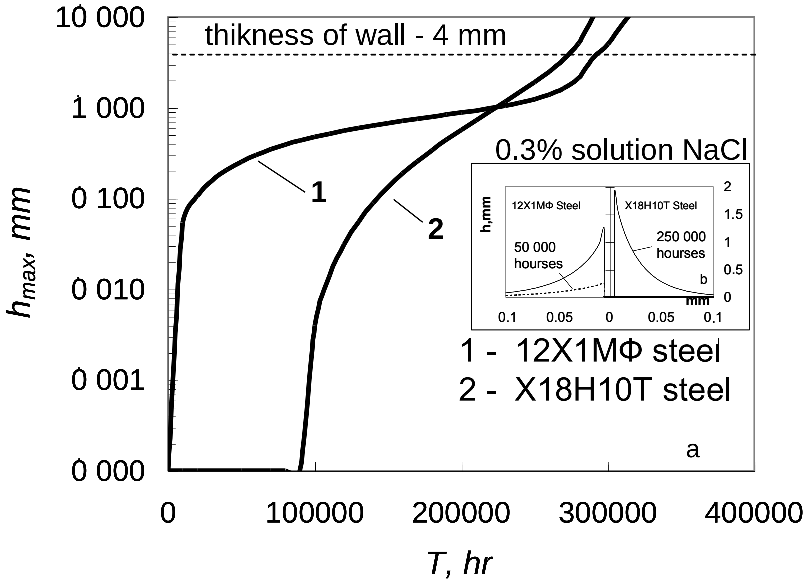


Fig. 3. Maximum depth of corrosion damaging of welded joint components of dissimilar pipes (*a*) in the 0.3% NaCl with dependence on planned exploitation time: 1 – 12X1MΦ steel, 2– X18H10T steel.
The distribution of depth of corrosion damaging (*b*) on the base of 50 000 and 250 000 hr.

Strength and life-time assessments

The two cases were modelled in this work for the strength assessment. These possible cases were considered: first – defect as notch with finite radius, and second – defect as crack. The durability of each component of welded dissimilar pipe with growing corrosion defect was determined as the time for achieving conditions: $\sigma_{\max} = \sigma_{YS}$ and/or $K_I = K_{IC}$.

For notch the maximum stress criterion was applied, i.e.: $\sigma_{\max} \le \sigma_{YS}$, where $\sigma_{\max}$ is maximum stress at notch tip; σ_{YS} is yield stress of composing materials (Fig. 4). For each of investigated materials criterial values of σ_{YS} are [2]: $\sigma_{YS} = 299\,MPa$ for 12X1MΦ steel and $\sigma_{YS} = 260\,MPa$ for 12X18H10T.

Here $\sigma_{\max}$ was calculated using equation [7]:

$$\sigma_{\max} = 2\sigma_n \sqrt{\frac{a}{\rho}}\,; \qquad (3)$$

where: σ_n is normal stress; ρ – radius of notch (here $\rho = 0.1$).

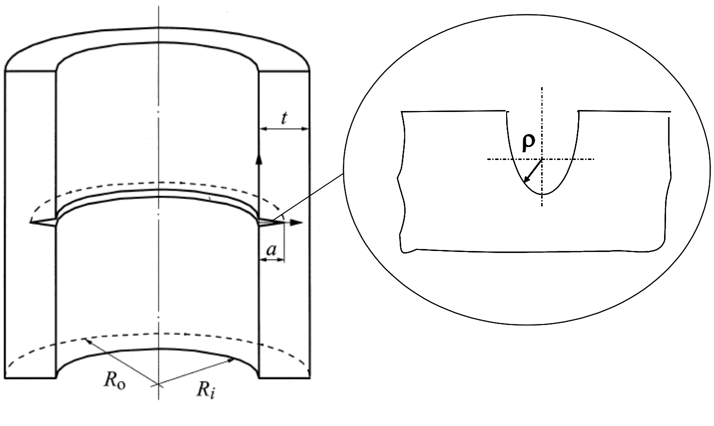


Fig. 4. The first case: defect as notch

Also it was used the assessment that realises according to well-known criterion of brittle fracture mechanics [1, 8]: $K_I \le K_{IC}$, where K_{IC} is a cyclic fracture toughness [8]. On this ground, the critical defect depth a_{IC} that defines the criterion of the “critical” crack-like defects will be the condition: $a \le a_{IC}\left(K_{IC}\right)$.

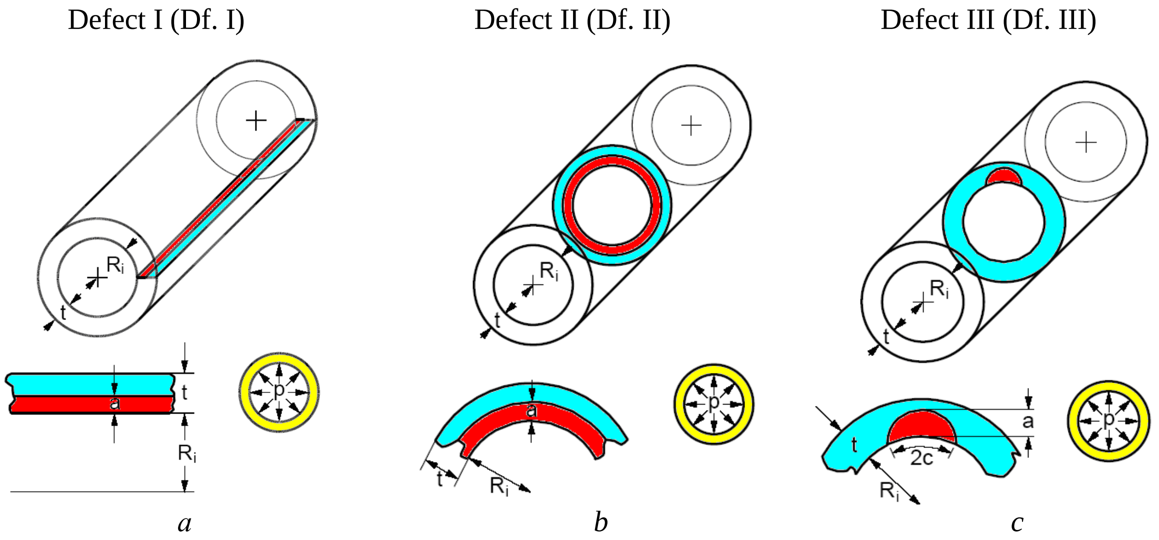
Thus, all detected crack-like defects in the pipelines by depth about $a \approx a_{IC}$ can be considered as critically dangerous, because of existing of high probability for their spontaneous growth that will lead to catastrophic failure of pipeline.

Fig 5 presents a few possible potential defects, that considered on this work, namely:

1) on the first stages of destruction longitudinal defect on the internal surface of cylinder under internal pressure (Fig. 5a);

2) circumferential defect on the internal surface of cylinder under internal pressure (Fig. 5b);

3) axial defect with semielliptical surface defect on the internal surface of cylinder under internal pressure (Fig. 5c).



a *b* *c*

Fig. 5. Potential defects on the internal surface of pipeline: a) longitudinal defect (Df. I); b) circumferential defect (Df. II); c) semielliptical defect (Df. III). R_i – radius internal; a – defect depth; t – cylinder wall thickness; $R_a = R_i + a$; p – internal pressure; $2c$ – defect width.

For the first case (Df. I) stress intensity factor (SIF) was calculated using functions [1, 9]:

$$K_I = 2p\frac{R_a{}^2}{R_a{}^2 - R_i{}^2}F\sqrt{\pi a}\ ; \tag{4}$$

where:

$$F = \left(\frac{t}{R_i} - X_2\right)\left(\frac{F_1 - F_2}{0.1}\right) + F_2;\ F_1 = 1.1202 + 0.44395\left(\frac{a}{t}\right) + 2.7289\left(\frac{a}{t}\right)^2 + 2.5313\left(\frac{a}{t}\right)^3;$$

$$F_2 = 1.11432 + 1.54228\left(\frac{a}{t}\right) + 1.5241\left(\frac{a}{t}\right)^2 + 5.480\left(\frac{a}{t}\right)^3.$$

For the second case SIF (Df. II) was calculated using equations [1, 10]:

$$K_I = \sigma\frac{F}{\sqrt{1 - \dfrac{a}{t}}}\sqrt{\pi a}\ ; \tag{5}$$

where:

$$F = 0.8153\left(\frac{a}{t}\right)^6 - 24.875\left(\frac{a}{t}\right)^5 + 39.8\left(\frac{a}{t}\right)^4 - 24.52\left(\frac{a}{t}\right)^3 + 9.0982\left(\frac{a}{t}\right)^2 - 0.7477\left(\frac{a}{t}\right) + 1.1192;$$

$$\sigma = \frac{p}{\left(\frac{R_a}{R_i}\right)^2 - 1}.$$

For the third case (Df. III) SIF was calculated using functions [1, 11]:

$$K_I = \sigma\left(1 + \left(\left(\frac{R_a}{R_i}\right)^2 - 1\right)\right) Y_a \sqrt{a}\,; \qquad (6)$$

where:

$$\sigma = \frac{p}{\left(\frac{R_a}{R_i}\right)^2 - 1}; \quad Y_a = \frac{1}{\sqrt{1 - \frac{a}{t}}}(Y_1 + Y_2 + Y_3);$$

$$Y_1 = 1.6561 - 0.3944\left(\frac{a}{c}\right) - 0.46115\left(\frac{a}{c}\right)^2 + 0.33664\left(\frac{a}{c}\right)^3 +$$

$$+\frac{a}{t}\left[-0.78383 - 0.4868\left(\frac{a}{c}\right) - 0.57149\left(\frac{a}{c}\right)^2 + 1.1149\left(\frac{a}{c}\right)^3\right];$$

$$Y_2 = \left(\frac{a}{t}\right)^2\left[0.04206 + 13.568\left(\frac{a}{c}\right) - 23.844\left(\frac{a}{c}\right)^2 + 11.147\left(\frac{a}{c}\right)^3\right];$$

$$Y_3 = \left(\frac{a}{t}\right)^3\left[0.48946 - 18.201\left(\frac{a}{c}\right) + 33.969\left(\frac{a}{c}\right)^2 - 17.301\left(\frac{a}{c}\right)^3\right].$$

Criterion data of the stress intensity factor of different steels were taken from work [2]: $K_{IC} = 20.95 MPa\cdot\sqrt{m}$ for 12X1MФ steel and $K_{IC} = 24.89 MPa\cdot\sqrt{m}$ for 12X18H10T steel.
For all considered cases the specific values a_*, at which the conditions are valid were determinated (Table 1):

$$a_* \cong h(\sigma = \sigma_{YS}); \qquad a_* \cong h(K_I = K_{IC}). \qquad (7)$$

However it should be noted that such kind a defects in the investigated objects meets only on the initial stages of destruction, and, mainly, length of defect does not come to the threateningly value, and stops approximately on a value of a 0.5 mm, after that destruction takes place on the internal surface of pipeline near the weld zone both in case of 12X1MФ steel and in 12X18H10T steel.
A circumferential defect becomes dangerous after the depths of approximately 3.91 mm (12X1MФ steel) and 3.96 mm (12X18H10T). Time to achieve such value according to the equation (5) for 12X1MФ steel is 297 400 hr, and for the X18H10T steel – 282 000 hr.
However according to the results of calculations it is necessary to undertake an additional study for this specific case, as the extraordinarily small is "safe" thickness of wall of pipeline. Regarding to the semieliptical defect, the value K_{IC} for both steels is arrived at approximately after the depths

of defect of 2.02 mm (12X1MΦ steel) and 2.11 mm (12X18H10T), and accordingly time to achieve such value for 12X1MΦ steel is 291 700 hr. and for 12X18H10T steel – 266 400 hr.

Table 1. The specific values a_*

12X1MΦ steel		12X18H10T steel	
$a_* \cong h(\sigma = \sigma_{YS})$, mm	$a_* \cong h(K_I = K_{IC})$, mm	$a_* \cong h(\sigma = \sigma_{YS})$, mm	$a_* \cong h(K_I = K_{IC})$, mm
3.82	Df. I: 1.60	3.79	Df. I: 2.16
	Df. II: 3.91		Df. II: 3.96
	Df. III: 2.02		Df. III: 2.11

The calculations for the assessment of durability of investigated welded joint presented on Table 2 were conducted on the base of criteria (7): $a_* \cong h\big|_{(K_I = K_{IC})}$, $a_* \cong h\big|_{(\sigma_{\max} = \sigma_{YS})}$ and $a_* \cong h\big|_{(h = 4\,mm)}$. Last criterion is the rust-through damage of welded joint.

Table 2. The predicted life-time of welded joint components

12X1MΦ steel		12X18H10T steel	
Criterion $a_* \cong h\big|_{(K_I = K_{IC})}$, hours			
$K_{IC} = 20.95\,MPa \cdot \sqrt{m}$		$K_{IC} = 24.89\,MPa \cdot \sqrt{m}$	
Df. I	288 800	Df. I	267 100
Df. II	297 400	Df. II	282 000
Df. III	291 700	Df. III	266 400
Criterion $a_* \cong h\big|_{(\sigma_{\max} = \sigma_{YS})}$, hours			
$\sigma_{YS} = 299\,MPa$	297 200	$\sigma_{YS} = 260\,MPa$	281 600
Criterion $a_* \cong h\big|_{(h = 4\,mm)}$, hours			
297 600		282 200	

The time values to achieving the K_{IC} of modelled defects, σ_{YS} the maximum stress at notch tip values and the maximum depth of damage of pipe wall external side, i.e. when the through corrosion is observed are presented on the Table 2. With regard to the proximity of time values we can assert that the investigated approaches are valid.

Using the data from the Table 2 we can assess the durability of investigated welded joint in the given conditions using the "K_{IC}" criteria since time to achieve the critical value of K_{IC} parameter is less then time to achieve the critical value of σ_{YS} parameter. Moreover the defect Df. 1 is more dangerous then defects Df. 2 and Df. 3. However it must be noted that defects Df. 1 and Df. 3 are close by values in both damaged components of welded joint. Therefore it is necessary to trace the character of damage in process of its increasing, since defect Df. 1 and defect Df. 3 have different geometry and the possibility of appearance of defect Df. 3 is higher then defect Df. 1. But at some moment of exploitation defect Df. 1 stops its growth and there is high probability of appearance of defects Df. 2 and Df. 3 not along the welded joint component at some distance from the welded zone but directly close to the welded zone. It would be interesting to practically define the "transition" of one defect to another. In our specific case such kind of "transition" occurs when the a_{IC} achieves the value of 0.5 mm (Fig. 3 b). Though the only one experimental database at specific experimental conditions is considered here. According to such aspects it can be recommended that under experimental conditions it is reasonable to make the assessment of durability of investigated welded joint using the characteristic of time to achieve the critical value of parameter a_{IC} in the defect Df. 3. Still it is necessary to trace the potential probability of transition the defect № 1 to other defects directly near the welded zone and to define the value of a_{IC} parameter at which such transition is possible.

Conclusions

The calculating-experimental approach to durability the development of corrosion damaging of combined welded joint of austenitic and pearlitic steels that gives adequate enough durability results is presented. It was analysed different criteria and potential defects in such kind of objects. Given approach may be used for the durability assessments of damage development of such like of objects during its exploitation.

It would be expedient to describe the time variation of experimentally obtained basic electrochemical parameters with more intricate dependence than linear to improve the accuracy of durability assessments, that corresponds the real situation.

References

[1] Dmytrakh I. M., Vainman A. B., Stashchuk M. H. and Toth L. Reliability and durability of structural elements for heat-and-power engineering equipment. Reference manual /Editor I. M. Dmytrakh – Kiev: Publishing House of NASU “Academperiodyka” – 2005 – 378 p. (in Ukrainian).

[2] Dmytrakh I. M., Panasyuk V. V. An influence of the corrosive environments on local fracture of the metals near the stress concentrators - Lviv: National Academy of Sciences of Ukraine. Karpenko Physico-Mechanical Institute - 1999 -341p (in Ukrainian).

[3] Pan’ko I.M. Theoretical bases of engineering methods for estimation of crack growth resistance of materials and structural elements // Lviv: National Academy of Sciences of Ukraine. Karpenko Physico-Mechanical Institute, 2000. – 280 p.

[4] Sttat M., Duc Khoi Vu Limit loads of circumferentially flawed pipes and cylindrical vessels under internal pressure // Inernational Journal of Pressure Vessels and Piping. – 83. – 2006 pp. 188-196

[5] Dmytrakh I., Bilyy O. and Leshchak R. On assessment of corrosion damaging depth on pipes internal surface of water-steam circuit elements // Mechanical Engineering.—№4.—2007 p.—P. 3–6. (in Ukrainian).

[6] Dmytrakh I., Kolodiy B., Bilyy O. and Leshchak R. Kinetics assessment of localised corrosion damages in pipe welds of water-steam circuit elements / Physicochemical Mechanics of Materials .—2006.—Special edition. № 5. – P. 310–315 (in Ukrainian).

[7] The stress calculation standards of nuclear power plants equipment and pipelines (ПНАЭ Г-7-002-86) / Gosatomenergonadzor USSR. – Moskau: Energoatomizdat, 1989. – 525 p. – (Regulations and standards in nuclear power).

[8] Dmytrakh I., Bilyy O. and Barna R. Diagrams for structural integrity assessment of heat-and-power-engineering pipelines with corrosion fatigue defects // Materials of the 4th international conference “Fracture mechanics of materials and structural integrity” – Lviv. – 2009. – P. 747-756.

[9] Kumar V., German M.D. and Shih C.F. An Engineering Approach for Elastic-Plastic Fracture Analysis // EPRI-Report NP-1931, July 1981.

[10] Mettu S.R. and Forman R.G., Analysis of Circumferential Cracks in Circular Cylinders using the Weight Function Method // ASTM STP 1189, 1993, pp. 417-440.

[11] Lim E.Y., Dedhia D.D., and Harris D.O. Approximate Influence Functions for Part-Circumferential Interior Surface Cracks in Pipes // ASTM STP 791, pp. I-281 - I-296.