

THE INFLUENCE OF SERVICE LIFE AND CORROSIVE
ENVIRONMENT ON THE CRACK GROWTH RESISTANCE
OF THE WELDED JOINTS OF PIPE STEEL

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Abstract

This paper presents investigation results of the service life and the corrosive environment influence on the crack growth resistance of welded joints in X60 API 5L pipe steel, commonly used in gas main pipelines. Using the fracture mechanics approaches, which are sensitive to the influence of the different operational factors in the material, the crack growth resistance in the base metal, heat-affected zone (HAZ), and metal weld was established and compared. It was found that the material of the HAZ has the lowest fatigue and corrosion-fatigue fracture resistance. Degradation changes in the steel enhance this tendency. Comparative studies were carried out in air and in the NS4 solution simulating neutral underground water.

Key words: gas main pipelines, welded joints, low-alloy carbon steel, corrosive environment, cyclic loading, fatigue crack, corrosion-fatigue crack, crack growth rate, stress intensity factor

Introduction. The total length of gas main pipelines in the world, piped in 120 countries, is 3 500 000 km [1]. In particular, for example, as for 2013, in the USA this length was 1 046 000 km, in Canada – 100 000 km, in China – 86 000 km, in Ukraine – 22 000 km, in Germany – 13 000 km, etc. In general, the gas main pipeline system in the world entered the period of intensive ageing, since the beginning of its operation falls in the 60s–80s of the last century, which is evidenced

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by numerous emergencies, which pose a great threat to the population, the environment, and engineering structures. In particular, 1411 failures were recorded on the European Gas Transmission System (EGIG) pipelines, which operated for 50 years (from 1970 to 2019), i.e., the total number of failures for this period was 0.29 accidents/year/1000 km [2]. According to the US Pipeline and Materials Safety Administration (PHMSA) data, 661 accidents were recorded on US gas pipelines over 20 years (from 2003 to 2022). According to the UK Overland Pipeline Operators Association (UKOPA), 205 accidents were recorded on the pipelines over the period from 1962 to 2020, i.e., the total number of failures for this period is 0.20 accidents/year/1000 km [3].

Analysis of literature sources [2–4] shows that gas main pipeline emergencies occur for various reasons, which in particular include degradation of steel properties, arduous conditions and operating modes, metal corrosion, defects initiation and development, etc. Today, the tendency for failure increases with the increase in gas main pipeline operation time observed in the world. It is worth noting that in a significant number (10–25%) the cause of the gas main pipelines emergencies increase is the welded joints (WJ) fracture [2–4] since the gas main pipelines welded joints are particularly sensitive to the action of corrosive and hydrogen charging environments [5, 6]. The problem of embrittlement [8–10] of the gas main pipe material, including welded joints, due to thermal influence, which causes structural changes, redistribution of detrimental impurities, and residual stresses, is known. In addition, WJ have high electrochemical heterogeneity, due to which local corrosion processes both in the metal of the heat-affected zone (HAZ) and the weld metal (WM) are enhanced compared to the base metal (BM). Mechanical properties are determined, and the crack growth resistance of the X60 API 5L pipe steel of separate zones is evaluated using the fracture mechanics approaches of materials sensitive to operational factors. It is possible to predict the residual life of pipelines, improve diagnostic methods, and increase the safety of the gas main pipelines operation based on the obtained results.

Material and methodology. The metal of the elements of two longitudinal welded pipes $D = 1220$ mm, $t = 14$ mm cut from the stock pipe (non-operated pipe) and pipes after 45 years of operation, were studied.

The pipes are made of hot-rolled sheets of low-alloyed carbon steel X60 (Standard American Petroleum Institute Specification 5L). The chemical composition of API 5L X60 steel is as follows (mass%): ≤ 0.15 C; ≤ 0.45 Si; ≤ 1.7 Mn; ≤ 0.025 P; ≤ 0.015 S; ≤ 0.05 Nb; ≤ 0.1 V; ≤ 0.06 Ti; ≤ 0.15 – 0.5 Cr; ≤ 0.8 Ni; ≤ 0.45 Cu; ≤ 0.45 N; ≤ 0.2 Mo; Fe – balance.

The mechanical properties of the steel were determined according to standard test methods [11], and the microhardness according to ASTM E384. The fatigue crack growth rate was investigated according to the known method [12, 13].

The size of the WJ zones, namely BM, HAZ and WM zones, were determined by measuring the microhardness according to the indentation scheme (Fig. 1b, e),

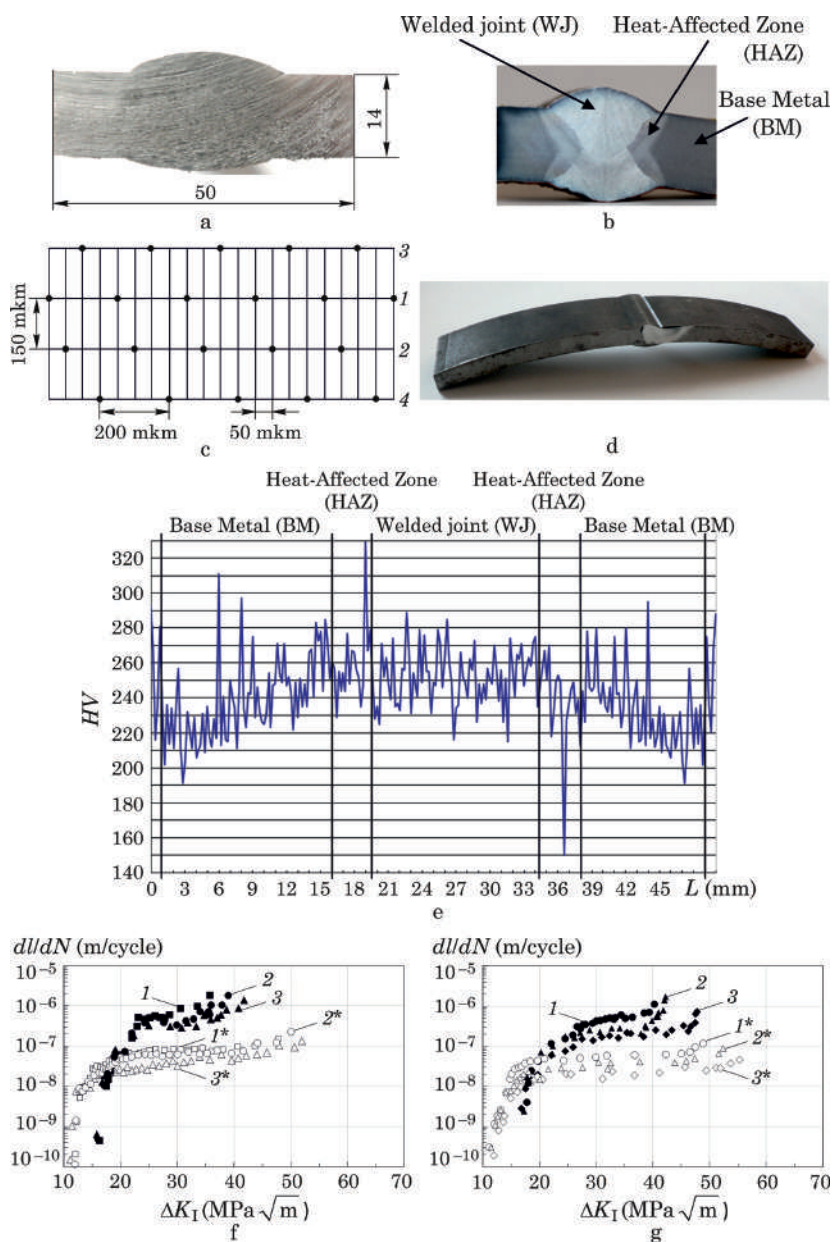


Fig. 1. The investigation scheme: **a** is the general view of the studied WJ; **b** its zones; **c** is the scheme of applying pricks with a diamond pyramid; **d** is a general view of the arched specimen cut from the gas main pipeline in the radial direction, containing a concentrator applied in the HAZ zone of the WJ; **e** is the microhardness of the studied specimen along the generating zone of the WJ (BM–HAZ–WM–HAZ–BM); the diagram of the cyclic crack growth resistance of **f** operated and **g** non-operated pipes in the NS4 solution (1, 2, 3), and air (1*, 2*, 3*): HAZ (1, 1*), WM (2, 2*), and BM (3, 3*) of the pipe at $R = 0.8$ and $f = 1$ Hz

which allows determining of the microhardness of the surface with a discretization of 50 μm , satisfying the measurement condition (the distance between the indentations should be at least 3–5 diagonals of the impression).

The workpiece for arched specimens measuring $50 \times 14 \times 300 \text{ mm}$ were cut from fragments of two types of pipes. A V-shaped stress concentrator with a depth of the pipe wall thickness 10% (Fig. 1a, d) was applied after mechanical treatment according to previous studies on one of the WJ zones (BM, HAZ, and WM). After that, the working surface of the specimen was polished, and a fatigue crack with a length of 20% of the pipe wall thickness was formed on a high-frequency cantilever bending machine at a load 10–15% less than the initial one in the experiment.

The tests were carried out at room temperature $T = 20^\circ\text{C}$ and specimens cyclic loading by cantilever bending with a frequency $f = 1 \text{ Hz}$ at a sinusoidal shape of the asymmetric load cycle ($R = 0.8$), which was selected based on the operating conditions analysis [14].

When constructing a cyclic crack growth resistance diagram, each value of the crack growth rate da/dN was set according to the value of the stress intensity factor (SIF) ΔK_I [6].

When studying the arched specimens containing an external edge crack as it developed deep into the pipe wall, the SIF ΔK_I value at its tip was determined according to the equation [15]:

$$(1) \quad \Delta K_I = \frac{2\sigma t}{R_{\text{intern}}} \times \frac{R_a^2}{(R_a^2 - R_{\text{intern}}^2)} \times F \times \sqrt{\pi a},$$

where $F = F_2 + \left(\frac{t}{R_{\text{intern}}} - 0.1 \right) \times \left(\frac{F_1 - F_2}{0.1} \right)$, $R_a = R_{\text{intern}} + t - a$, σ is the normal stress, t is the height of the specimen (thickness of the pipe wall), a is the crack length (depth),

$$F_1 = 1.1202 + 0.44395 \left(\frac{a}{t} \right) + 2.7289 \left(\frac{a}{t} \right)^2 + 2.5313 \left(\frac{a}{t} \right)^3,$$

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

The fatigue crack growth resistance of the test specimens was studied in air and an NS4 model aqueous solution [15] simulating underground water in neutral soil conditions (pH 6.7). The chemical composition of this environment is as follows (g/L): 0.122 KCl; 0.483 NaHCO₃; 0.137 CaCl₂ × 6H₂O; 0.131 MgSO₄ × 7H₂O.

Results and discussion. According to the scheme (Fig. 1c), the gas main pipeline WJ microhardness was determined (Fig. 1e). It was established that the length of the fusion zone, i.e., the WM zone in this WJ, is 15 mm, and HAZ from the BM side is 3.5 mm.

The regularities of the corrosion-fatigue cracks propagation in the WJ were studied, taking into account the peculiarities of the stress-strain state, the influence of groundwater and pressure fluctuations in the gas main pipeline

($R = 0.8$) [14], as well as the results of experimental determination of the WJ zones parameters.

The results of experimental studies of the BM zone of the WJ non-operated pipe and the pipe after 45 years of operation in air and in NS4 solution, as well as in the HAZ and BM, are presented in Fig. 1f, g, and in Tables 1–3.

Comparison of the obtained results showed a slight difference in the characteristics of cyclic corrosion crack growth resistance of pipe material after 45 years of operation and a non-operated pipe made of X60 API 5L steel (see Table 1). Here, the threshold stress intensity factors ΔK_{th} are practically equal, and the critical stress intensity factors ΔK_{fc} do not differ significantly from each other. It was found that the significant influence of the model corrosion environment is observed only at the stage of corrosion-fatigue crack propagation for pipe material after 45 years of operation in the HAZ, which is confirmed by slightly higher n and C parameters in the Paris power dependence (see Table 1) [12], i.e., by a greater slope of the second section of the diagram. In the case of corrosion-fatigue crack propagation for pipe material after 45 years of operation in the studied regions of WM and BM, an insignificant difference in the n and C parameters in the Paris power dependence was established.

It is worth noting that the fatigue crack growth resistance in the pipe material after 45 years of operation and a non-operated pipe of the studied WJ zones (BM, HAZ, and WM) in air is characterised by a lower slope compared to the similar ones in the NS4 solution (see Table 1).

T a b l e 1

Characteristics of cyclic crack growth resistance of the pipe steel after 45 years of operation (OM) and non-operated pipe (NM) made of X60 API 5L steel

WJ zone	Environment	$C, \left[\frac{\text{mm}}{\text{cycle}} \times (\text{MPa}\sqrt{\text{m}})^n \right]$	n	$\Delta K_{th}, [\text{MPa}\sqrt{\text{m}}]$	$\Delta K_{fc}, [\text{MPa}\sqrt{\text{m}}]$
OM: HAZ	NS4	7.21×10^{-17}	6.85	15.81	36.18
	air	3.91×10^{-10}	1.56	11.72	48.39
OM: WM	NS4	1.99×10^{-14}	4.93	15.93	39.34
	air	3.10×10^{-10}	1.57	11.62	51.47
OM: BM	NS4	3.06×10^{-13}	4.04	15.47	42.08
	air	3.69×10^{-10}	1.38	10.98	53.14
NM: HAZ	NS4	5.18×10^{-14}	4.60	16.75	41.27
	air	1.57×10^{-9}	1.04	10.86	49.35
NM: WM	NS4	3.32×10^{-14}	3.91	16.84	43.35
	air	6.04×10^{-10}	1.17	11.24	54.76
NM: BM	NS4	1.57×10^{-12}	3.26	16.53	48.05
	air	2.90×10^{-10}	1.45	11.46	59.12

In general, pipe material after 45 years of operation in the NS4 solution has a slightly lower crack propagation resistance compared to a non-operated pipe (see Fig. 1f, g).

The analysis of the obtained experimental data was carried out by estimating the corrosion-fatigue crack growth rate for different WJ sections (Fig. 1f, g), which corresponded to the average-amplitude sections of the cyclic crack growth resistance diagrams (Paris sections [17]) at an average SIF range $\Delta K_I = 30 \text{ MPa}\sqrt{\text{m}}$.

A comparative assessment of the corrosion-fatigue crack growth propagation rate in the average-amplitude section was carried out for each of the studied WJ zones (BM, HAZ, and WM). Table 2 presents the V_{NS4}^* and V_{air}^* values, and their comparative assessment for different “gas main pipelines metal in the vicinity of the WJ-environment” systems.

Analysis of the results shown in (Fig. 1f, g) and presented in Tables 1 and 2 allows us to conclude that the lowest crack growth resistance is in the HAZ. This is typical of both fatigue and corrosion-fatigue fracture, and is also observed for both materials after 45 years of operation, and a non-operated pipe steel.

The influence of the operation time was quantitatively estimated by the crack growth rates dc/dN in the model corrosion environment (V_{NS4}^*) and in air (V_{air}^*) ratio, which correspond to the values of the average-amplitude section of the cyclic crack growth resistance diagram at SIF range $\Delta K_I = 30 \text{ MPa}\sqrt{\text{m}}$:

$$(2) \quad k_e = V_{\text{NS4}}^{\text{EM}}/V_{\text{NS4}}^{\text{HM}}, \quad k_a = V_{\text{air}}^{\text{EM}}/V_{\text{air}}^{\text{NM}}.$$

The results in Table 3 indicate that BM in air and in the NS4 solution undergoes the greatest degradation changes.

T a b l e 2

Relative change of rates in the average-amplitude section of the cyclic crack growth resistance diagrams of metals WJs at the SIF range $\Delta K_I = 30 \text{ MPa}\sqrt{\text{m}}$

“WJ-environment” system	$V_{\text{NS4(air)}}^{\text{HAZ}}/V_{\text{NS4(air)}}^{\text{WM}}/V_{\text{NS4(air)}}^{\text{BM}}$ [m/cycle]	$\frac{V_{\text{NS4(air)}}^{\text{HAZ}}}{V_{\text{NS4(air)}}^{\text{WM}}}/\frac{V_{\text{NS4(air)}}^{\text{WM}}}{V_{\text{NS4(air)}}^{\text{BM}}}/\frac{V_{\text{NS4(air)}}^{\text{BM}}}{V_{\text{NS4(air)}}^{\text{BM}}}$
OM – NS4	$7.27 \times 10^{-7}/3.74 \times 10^{-7}/3.23 \times 10^{-7}$	2.24/1.16/1
NM – NS4	$4.28 \times 10^{-7}/2.53 \times 10^{-7}/1.63 \times 10^{-7}$	2.63/1.55/1
OM – air	$8.19 \times 10^{-8}/6.18 \times 10^{-8}/3.81 \times 10^{-8}$	2.18/1.62/1
NM – air	$5.27 \times 10^{-8}/3.81 \times 10^{-8}/1.95 \times 10^{-8}$	2.70/1.95/1

T a b l e 3

Comparison of crack growth rates dc/dN in air and in the NS4 solution

WJ zone	$V_{\text{NS4}}^{\text{EM}}/V_{\text{NS4}}^{\text{HM}}$	k_e	$V_{\text{air}}^{\text{EM}}/V_{\text{air}}^{\text{NM}}$	k_a
HAZ	$7.27 \times 10^{-7} / 4.28 \times 10^{-7}$	1.70	$8.19 \times 10^{-8} / 5.27 \times 10^{-8}$	1.55
WM	$3.74 \times 10^{-7} / 2.53 \times 10^{-7}$	1.49	$6.18 \times 10^{-8} / 3.81 \times 10^{-8}$	1.62
BM	$3.23 \times 10^{-7} / 1.63 \times 10^{-7}$	1.98	$3.76 \times 10^{-8} / 1.95 \times 10^{-8}$	1.92

Conclusion. The mechanical properties of materials, sensitive to operational factors, taking into account degradation changes in structural steels, the influence of environments, etc., were determined, and the crack growth resistance of the X60 API 5L pipe steel welded joints zones was assessed using the fracture mechanics approaches.

The geometric dimensions of the heat-affected zones, as well as the weld metal of the studied longitudinal welded pipes, were localised and determined. The crack-like defects growth resistance of the material was assessed separately for each of these zones (BM, HAZ, and WM). It was established that the HAZ has more than twice less fatigue and corrosion-fatigue fracture resistance compared to BM, which is associated with microstructural changes, residual stresses, and electrochemical heterogeneity of the zone.

Long-term operation (for 45 years) reduces the corrosion-fatigue fracture resistance of the HAZ material, as evidenced by the increase in the fatigue crack growth rate in the NS4 solution, for both operated and non-operated materials. The base metal is most sensitive to corrosion, which is an important factor in assessing the residual life of pipelines.

The obtained results can be used [18–20] to predict the residual life of pipelines, improve diagnostic methods, and increase the gas main pipelines' operation safety.

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