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STUDY OF INTERGRANULAR CORROSION CRACKING IN WELDED JOINTS OF CHORNOBYL NPP PIPELINES. MATERIALS SCIENCE ASPECT

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ABSTRACT

Stress corrosion cracking, similar to intergranular corrosion in austenitic steel welds, primarily affects grain boundaries in the heat-affected zone when exposed to a corrosive environment, leading to sensitization, i.e. reduction in structural integrity, which causes cracking and grain loss. The object of studies were specimens cut out of rings from the pipelines of Power Unit 3 of the Chernobyl NPP in the areas of damaged welded joints. Based on radiographic and ultrasonic testing of pipeline welds, as well as determination of the content of alloying elements in the tested specimens, mechanical properties, metallographic, fractographic and micro-X-ray spectral studies, including investigation of fracture surfaces of specimens that were cyclically loaded taking into account fatigue grooves, and with regard to solution of the problem of corrosion cracking of austenitic steels in boiling water reactors, a set of measures was developed, including long-term measures: replacement of steels with others, that are not prone to corrosion cracking; short-term measures: deposition of external weld coating, repair of defective areas, relieving residual stresses; temporary measures: justification of the admissibility of the defective weld for operation.

KEYWORDS: radiographic and ultrasonic testing of welded joints, intergranular corrosion, stress corrosion cracking, corrosion-resistant steel, pipelines, alloying elements, chromium carbides, fatigue grooves

INTRODUCTION

Stress corrosion cracking in welded joints (WJ), similar to intergranular corrosion (IGC), can occur almost without visual evidence of corrosion damage [1]. Metallographic and fractographic studies of fractures performed on damaged circumferential welds cut out from the pipelines of Unit 3 (pipelines of the 1st circuit with an outer diameter of 325 mm and a wall thickness of 16 mm) revealed an intergranular (at crack propagation in the heat-affected zone (HAZ)) and intragranular (at crack propagation along the weld metal) fracture pattern. The crack surfaces are oxidised. Significant corrosion damage with typical crack branching was observed in both cases [2, 3]. IGC is known to be a type of local corrosion of steels and alloys when a potential difference between the grain boundaries and the body of the grains occurs during the contact with the corrosive environment. This type of corrosion usually takes place when a phase precipitation from the solid solution occurs in the alloy. In most cases, the precipitation occurs more rapidly at the grain boundaries, the so-called sensitization, which results in the depletion of the material near the grain boundaries by the alloying element. Unlike other forms of corrosion (pitting, crevice and fretting corrosion), signs of intergranular corrosion in stainless steel are not always visible on the metal surface. Intergranular corrosion occurs at the microscopic level, affecting the metal structure itself, and requires certain conditions that can be avoided in some cases. The precipitation of chromium carbides at grain boundaries in austenitic stainless steels typically occurs at heating from 540 to 845 °C, which leads to a depletion of chromium at the grain boundaries and, consequently, increased corrosion sensitivity. The most frequently sensitization is caused by welding. In addition, the mentioned temperatures are most common during heat treatment or operation in a high-temperature environment.

Thus, intergranular corrosion in a stainless steel weld mainly affects the grain boundaries in the HAZ, which leads to a decrease in structural integrity, causing cracking and grain loss. At the same time, in welded structures made of ferritic steels, fracture occurs both in the area immediately adjacent to the weld place and in the weld itself. Ignoring the risks of intergranular corrosion can lead to catastrophic failure or partial failure of critical welded structures and various components of stainless steel structures, including NPP equipment, pipelines used in oil and gas transportation, etc.

INFLUENCE OF ALLOYING ELEMENTS ON THE IGC MECHANISM IN STAINLESS STEELS

Three classes of stainless steels are traditionally used: ferritic, martensitic and austenitic, and rarely two-

Table 1. Influence of alloying elements in steel based on anodic polarization curves of pure metals [3]

Value of potential E, V	Characteristic of the environment	Rate of metal solution in the series
–0.5	Strongly reducing	Ni < Mo< W < Fe < Cr < Mn
–0.05	Non-oxidizing	Mo < Cr < W < Ni < Fe < Mn
+0.2	Slightly oxidizing	Mo < Cr < W < Ni < Fe < Mn
+0.6	Medium oxidizing	Cr < Ni < Fe < W < Mo < Mn
+1.1	Oxidizing	Cr < Ni < Fe < W < Mo < Mn
+1.3	Highly oxidizing	Fe < Ni < W < Cr < Mo

phase. The largest group of all stainless steels includes austenitic corrosion-resistant steels, which account for 60–70 % of global consumption [4]. They usually contain 16–25 % Cr, 6–14 % Ni, sometimes 2–6 % Mo and a small amount of other elements. The most common example is 08Kh18N10T steel. It should be noted that 08Kh18N10T steel used for pipe manufacturing is an analogue of AISI321 stainless austenitic steel stabilized with titanium.

Chromium is the main alloying element in corrosion-resistant steels that ensures the passivation ability of steel over a wide range of potentials. The instability of chromium is manifested only in the potential range of –0.58 V in highly reducing environments and 1.3 V in highly oxidizing environments (Table 1).

The effect of chromium on IGC is closely related to carbide formation. At a constant quenching temperature, the minimum time τ_{min}, required for carbide formation depends on the diffusion rate of carbon and chromium. In the low temperature region, the appearance of IGC tendency is controlled by chromium diffusion, and at higher temperatures — by carbon diffusion. Since the ability of carbon to form carbides is determined by its thermodynamic activity, which is significantly influenced by the chemical composition of steel, the admissible carbon content depends on the

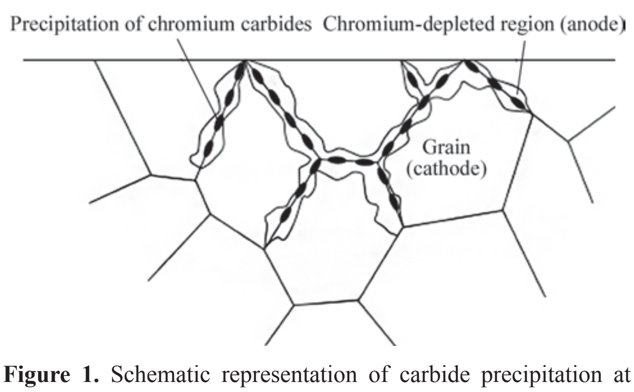

Figure 1. Schematic representation of carbide precipitation at grain boundaries in austenite [4]

content of such alloying elements in steel as nickel, molybdenum, etc.

Nickel, silicon and cobalt increase the activity of carbon, i.e. facilitate the formation of carbides; molybdenum, tungsten, vanadium, niobium and manganese decrease the activity of carbon, i.e. inhibit the formation of carbides. Nickel is introduced into corrosion-resistant steels to ensure the stability of the austenitic structure and to improve the corrosion resistance of steel mainly in reducing environments, although it has satisfactory corrosion resistance in a wide range of potentials. Molybdenum enhances the self-passivation ability of chromium-nickel steels and significantly increases their resistance in non-oxidizing and slightly oxidizing environments. In oxidizing and strongly oxidizing environments, the corrosion rate of molybdenum and molybdenum-rich phases is high (Table 1).

One of the most common ways to prevent IGC is to alloy corrosion-resistant steels with carbide-forming elements. The most stable carbides form titanium, niobium and tantalum, but stabilization with titanium and niobium is more commonly used [5]. According to the stoichiometric formula of titanium and niobium carbides, it is recommended to add titanium in 5-fold and niobium in 8–11-fold amount to bind carbon. The special TiC and NbC carbides are not completely insoluble. Their solubility depends on the degree of stabilization, but their dissolution temperature is significantly higher than that of chromium carbides. Compared to low-carbon steels, stabilized steels are prone to IGC in approximately the same temperature range, but in stabilized steels, the tendency to IGC disappears at long-term holding times. The latter is explained by the fact that in stabilized steels, depending on the degree of stabilization, a certain amount of $M_{23}C_6$ is formed initially, rather than a special TiC or NbC carbide due to the slow diffusion of titanium and niobium. As the holding time grows, TiC or NbC carbides are formed — chromium carbide dissolves and chromium depletion disappears.

Since the precipitation of carbides from the solid solution occurs faster at the grain boundaries (Figure 1), the material near the grain boundaries is depleted by the alloying element, creating a potential difference that promotes better dissolution of the alloy boundary zones. IGC is observed in Cr- and Cr–Ni steels and leads to a sharp decrease in alloy strength and ductility, which can cause a premature structural failure. IGC can be caused by slow cooling of the alloy through the dangerous temperature region and even long-term welding works. This does not occur during rapid cooling.

Thus, IGC of steels and alloys occurs when a potential difference between the grain boundaries and the grain body arises in contact with the corrosive environment, the electrolyte. In general, three main mechanisms of intergranular corrosion can be distinguished in corrosion-resistant Cr- and Cr–Ni steels:

- depletion of grain boundary areas with elements that determine the material's stability in this environment;
- low chemical stability of phases precipitated at the boundaries;
- segregation of surface-active elements at the grain boundaries that reduce the stability of the base in this environment.

The mentioned IGC mechanisms can operate simultaneously in different steels, but one of them has a decisive influence on the corrosion rate. Usually, a phase precipitation from the solid solution occurs.

INTERGRANULAR STRESS CORROSION CRACKING (ISCC)

The problem of corrosion cracking of welds of austenitic steels in boiling water reactors (BWR) and light water reactors (LWR) first arose in the 70s of the twentieth century [6]. Western countries and Japan faced the problem of cracking of welded joints of pipelines made of austenitic stainless steels at NPPs with LWR reactors in the early 70s of the twentieth century. In the United States, cracks were first detected at the Unit 2 of the Dresden NPP in September 1974. Later, the problem of corrosion cracking at US NPPs became a large-scale one. On average, 25 % of welded joints had cracks, with some units having a defect rate of 50 %.

In this regard, a special programme of technological, calculation and experimental works was developed [6] to solve the following issues:

- need in repair of detected cracks;
- flaw detection of all welds;
- assessment of the fatigue life of defective or repaired sections;

long-term solutions that include replacement of pipeline systems.

Large capital investments were aimed at searching for improvement measures. The following were suggested as the most affordable and reasonable:

- induction heating to relieve residual stresses;
- deposition of external welding coating;
- mechanical crimping of the outer pipe surface near the defective WJ.

As a long-term goal and as the main focus of combating the ISCC phenomenon, KWU Siemens began developing new types of steels that are not prone to sensitization and corrosion [7].

In Japan, the ISCC study was carried out as part of the national programme to ensure the reliability of pipeline systems, the main goal of which was:

- demonstration of the integrity of pipeline system during operation, taking into account both fatigue and, especially, ISCC with sufficient safety factors;
- verification of the concept of 'leak before failure' in pipeline systems;
- demonstration of effective protective devices in case of guillotine failure.

Thus, based on the inspection, the following set of measures was developed to solve the problem of corrosion cracking of austenitic steels in boiling reactors:

- long-term measures: replacement of steels with other steels not prone to corrosion cracking;
- short-term measures: deposition of external welded coating, repair of defective areas, removal of residual stresses;
- temporary measures: justification of the admissibility of the defective weld operation.

MATERIALS SCIENCE ASPECTS OF THE CONDITION OF Du300 PIPELINES OF ChNPP UNIT No. 3

Unit No. 3 of the Chernobyl Nuclear Power Plant (ChNPP) belongs to the second generation of 1000 MW reactors (RBMK-1000) and represents a heterogeneous channel-type thermal neutron reactor with a graphite moderator and boiling light water coolant. The RBMK-1000 has a thermal design typical of single-circuit boiling water reactors, consisting of channel pipes and pipelines of various diameters, which together form a repeated forced circulation circuit (RFCC), as well as a steam pipeline supplying steam to the turbines. Most of the pipelines of the Du300 RFCC (downflow pipelines (DP), pressure pipelines (PP), automatic reactor coolant system (ARCS), etc.) have an outer diameter of 325 mm, rated wall thickness of 16 mm and are made of austenitic steel stabilized with 08Kh18N10T titanium, which is an analogue of AISI 321 stainless austenitic steel.

During the shutdown of ChNPP Unit 3 for routine repair in 1997, a 100 % radiographic inspection of welds of the DP, PP and ARCS pipelines (Table 2) was performed. By then, the equipment of ChNPP unit No. 3 had reached the end of 99230.33 operating hours. In accordance with the Instruction [8] and on the basis of the "Work Programme for Cutting Out Sections of Unit 3 Pipelines to Investigate the Condition of Base Metal and Welded Joints after 100 Thous H of Operation", the pipeline sections were cut out. The cut out pipeline sections were in operation since December 1981.

Table 2. Results of radiographic inspection of welds of ChNPP Unit 3 safety system pipelines obtained in 1997

Type of pipelines	No. of premises	Number of welds tested	Number of defects detected	
			Cracks	Welded defects
Downflow pipelines	804/1 БС 21	120	9	4
	BS 22	96	9	6
	804/2 BS 11	96	21	10
	BS 12	120	17	4
	403/1 BS 21	84	7	–
	BS 22	84	6	3
	403/2 BS 11	84	9	6
	BS 12	84	11	6
	Total	768	89	39
Pressure pipelines	404/1	88	23	–
	404/2	88	17	3
	403/1	160	23	4
	403/2	160	17	3
	Total	496	80	10
Pipelines of the reactor emergency cooling system	404/1	15	4	2
	404/2	12	6	1
	405	51	14	6
	216	14	5	3
	02	95	1	2
	Total	187	30	14
Total		1451	199	63

The Programme included determination of mechanical properties (σ_t, σ_y, δ, ψ) and impact toughness at room temperature (20 °C) and 350 °C; hardness (*HB*) of the pipe cross-section; determination of the chemical composition of the base metal and welded joints; microstructure examination; determination of the cyclic crack resistance characteristics of the base metal and welded joint. During the radiation inspection of 1451 welded joints of DP, PP and ARCS of the Du300 pipelines, 199 defects in the form of cracks and 63 welding defects were detected. All detected defects were repaired in 1997. Since there was no confidence that all weld defects were detected by radiographic inspection, the ChNPP management decided to perform

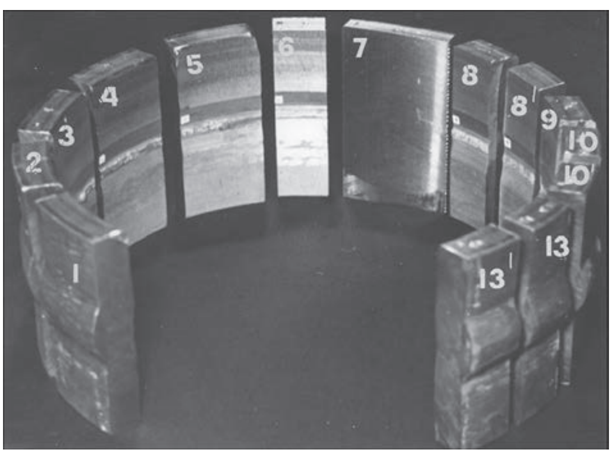

Figure 2. General appearance of a ring with a weld, cut into templates

Table 3. Results of ultrasonic testing of welds of pipelines of the safety system of ChNPP Unit 3 obtained in 1997–1998

Type of pipelines	No. of premises	Number of welds tested	Number of defects detected
Downflow pipelines	804/1 BS 21	107	9
	BS 22	81	7
	804/2 BS 11	65	6
	BS 12	99	19
	403/1 BS 21	77	12
	BS 22	75	11
	403/2 BS 11	69	9
	BS 12	67	9
	Total	640	82
Pressure pipelines	404/1	65	18
	404/2	68	17
	403/1	111	26
	403/2	118	32
	Total	368	93
Pipelines of the emergency reactor cooling system	404/1	9	–
	404/2	5	3
	405	31	2
	216	6	2
	02	92	1
	Total	143	8
Total		1145	183

100 % ultrasonic testing (UT) of the welds available for UT. UT results obtained during 1997–1998 are shown in Table 3.

Due to the fact that it was not possible to repair all the newly detected defects at ChNPP, it was decided to assess the ability of further operation of the ChNPP safety system pipelines with detected defects for another year (until the next routine repair).

In the process of testing damaged welded joints of pipelines, the following was studied:

- metal quality of welded pipes;
- areas of predominant cracks initiation and nature of their propagation;
- mechanism of open cracks propagation (fractography).

The object of studies was specimens cut out from rings (Figure 2) from ChNPP Unit 3 pipelines in the areas of damaged welded joints, including: 53 units of downflow pipelines, 32 units of pressure pipelines, and 4 units of ARCS.

Figure 2 shows a ring cut into templates containing a weld (in this case, weld No. 8 of the pressure pipeline). The templates are arranged in the same order as in the uncut ring, and the numbers indicated on the templates allow localizing subsequent investigations by referring to the corresponding template number.

The content of alloying elements in the studied specimens was determined using a Camascan scanning electron microscope with an X-ray spectrometer System 860 CP2-50 from Link System. To obtain

Table 4. Chemical composition (wt.%) of pipe metal made of 08Kh18N10T steel

Welded joint area	C	Mn	Si	Cr	Ni	S	P	Ti	Cu
Base metal on the left	0.08	1.41	0.55	19	10.17	–	0.035	0.4	0.07
Base metal on the right	0.08	0.99	0.23	19.28	10.21	0.018	–	0.428	0.3
Requirements in accordance with TU 14-3-197–73 for delivery in accordance with GOST 5632–72	≤ 0.08	≤ 1.5	≤ 0.8	17÷19	10÷11	≤ 0.02	≤ 0.035	5C÷0.06	≤ 0.3

Table 5. Mechanical properties of pipe specimens from the investigated 08Kh18N10T steel

Pipe specimens	*T*, °C	$\sigma_{0.2}$, MPa	σ_t, MPa	δ, %	ψ, %	*KCV*, kgs·m/cm^2
Diameter 325×16	+20	434 473 361	641 656 665	49.1 41.8 42.5	58.8 64.8 66.3	19.0 22.9 19.1

reliable results, measurements were made at several points. An example of the results is shown in Table 4.

THE MECHANICAL PROPERTIES

Were determined on plane or fivefold cylindrical specimens (type IV of GOST 1497–84) with a diameter of 4 mm in the temperature range of –196–+350 °C. Standardized tests for determining mechanical properties in the temperature range of 77–293 °C were carried out in a specialized Ala-Too unit and an Instron-1251 universal inspection machine, which were equipped with special cryo- and thermal chambers to create and maintain the appropriate test temperatures. A scheme of cutting specimens and their main dimensions are shown in Figure 3. The impact toughness was determined by the results of tests of Charpy specimens with a V-notch on a certified MK-30A pendulum tester in accordance with GOST 9454–78. In addition to impact tests of Charpy specimens, the ductile-brittle transition temperature (DBTT) was determined by the

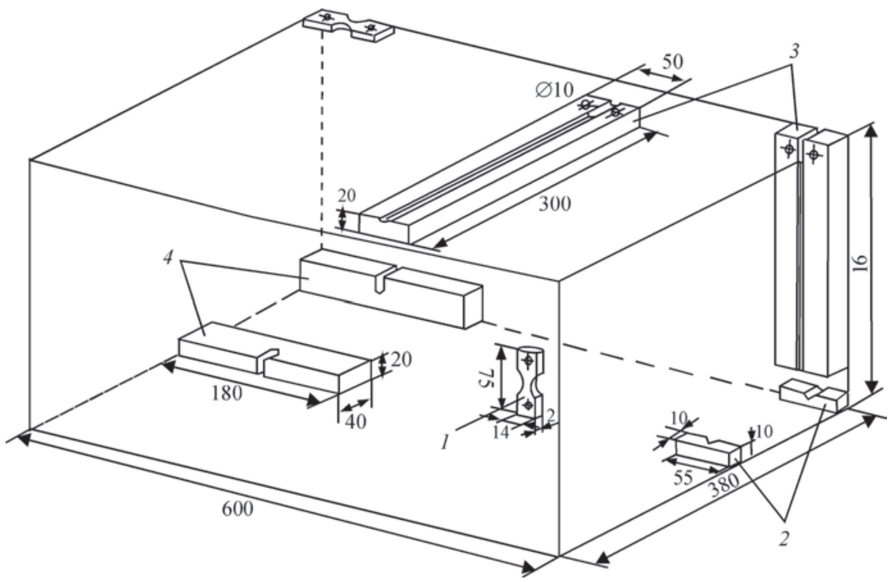

Figure 3. Scheme of cutting specimens and their basic dimensions

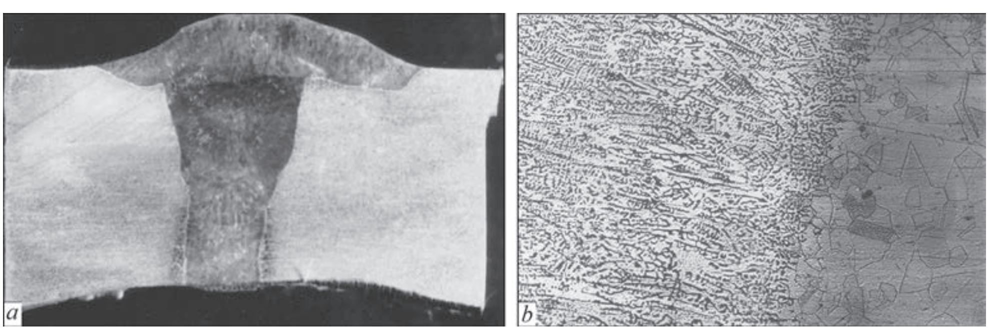

Figure 4. Structure of the pipeline material (325×16, 08Kh18N10T steel) at Unit 3 of the ChNPP after 100 thou h of operation: *a* — macrostructure, ×3; *b* — microstructure, ×100

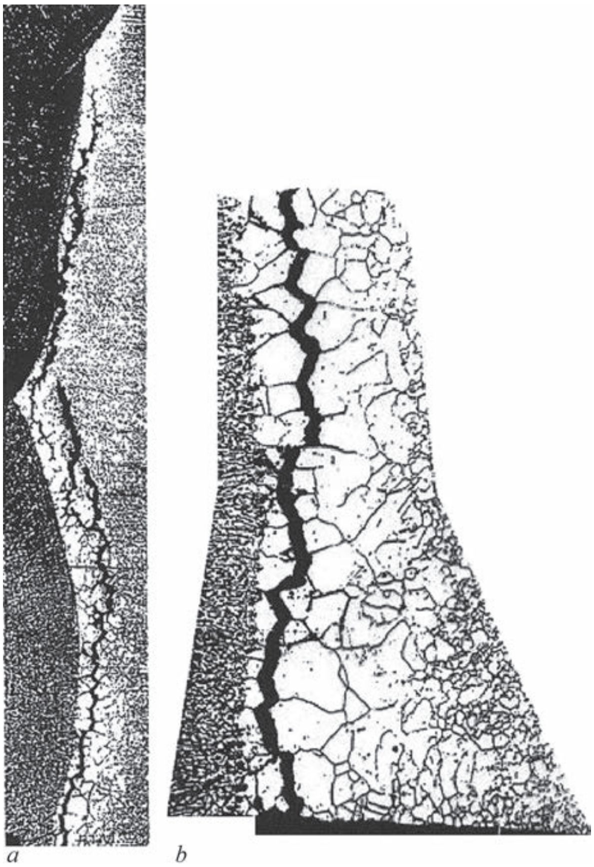

Figure 5. Appearance of a crack in the near-weld zone of welded joint: *a* — ×30; *b* — ×80

temperature dependence of the reduction in area and by X-ray analysis.

Some test results for pipe specimens made of 08Kh18N10T steel are shown in Table 5.

METALLOGRAPHIC EXAMINATIONS

Macrosections were made on the cutting surfaces (see Figure 2), followed by etching in 1 part HNO_3 +2 parts HCl reagent, which allowed revealing the contours and structure of the weld (Figure 4), as well as cracks, if any were present (Figure 5).

It should be noted that the susceptibility of steels to intergranular corrosion, which was determined by the standard procedure [9], was not detected even in defective welded joints. However, thorough metallographic examinations on templates cut out from the rings of downflow and pressure pipelines of the reactor's emergency cooling system revealed a narrow (up to 1 mm) zone of metal sensitization located along the fusion line (the zone of coarser austenitic grain). In this zone, the formation of a network of $Cr_{23}C_6$ carbides along the boundaries of austenitic grains was observed. To confirm this fact, micro-X-ray spectral analysis revealed an increased (up to 38 %) chromium content in a narrow zone at the boundaries of austenitic grains, while the chromium content in the grain body was 11–13 %.

Metallographic examinations made it possible to reveal cracks of circumferential orientation on the inner surface of the pipe (both in the weld and in the near-weld zone). The cracks observed in the near-weld zone were in the form of cracks with branches (Figure 5).

Branching cracks usually propagate deep into the base metal of the pipe intergranularly, along a narrow zone of the fusion line of austenitic grains that had grown during welding.

Crack initiation on the inner surface of the pipe had a multi-embryonic nature, and the propagation of main circumferential cracks occurred by merging of multilevel embryonic cracks. Cases of cracks location were observed on both sides of the weld.

FRACTOGRAPHIC STUDIES

Were carried out using a Camscan scanning electron microscope. These studies confirmed the intergranular (at crack growth in the HAZ) and intragranular (at crack growth along the weld metal) nature of crack propagation with numerous traces of corrosion impact on the grain boundary facets (Figure 6). Secondary cracks extending deep into the metal were observed on the fracture surface. Analysis of corrosion products on the fracture surface showed the presence of chlorine in the amount of 0.15 wt.%.

Fractographic and metallographic examinations of the crack surface cleaned of corrosion deposits showed that the main mechanism was intergranular fracture with crack branching typical of corrosion. On

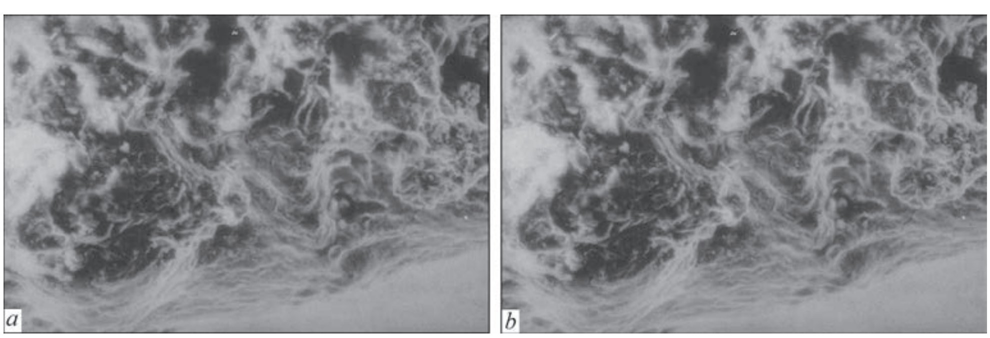

Figure 6. Microfractograms of a corrosion crack surface: *a* — before cleaning; *b* — after cleaning (average fatigue groove pitch $\Delta \approx 1.0$ μm)

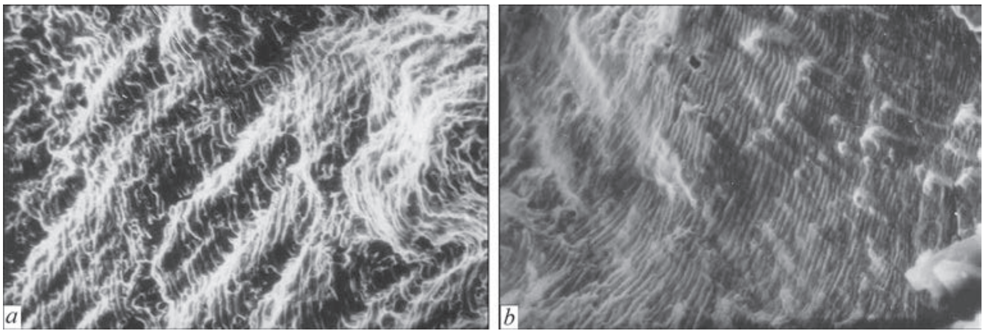

Figure 7. Fracture surface of the 08Kh18N10T steel specimen tested for cyclic crack resistance: *a* — at 20 °C, average fatigue groove pitch $\Delta \approx 1.5$ μm; *b* — at 50 °C, average fatigue groove pitch $\Delta \approx 2.0$ μm

the surface of the fracture, free of corrosion products, signs of fatigue fracture in the form of grooves were found, which can be detected even directly near the source of crack initiation (Figure 6, *b*). Distinct fatigue grooves are observed, which are an imprint of the crack front on each loading cycle, with a pitch of 0.4 μm. As a crack progressed, the pitch of the grooves increased to 1.0 μm.

Fractographic studies of the fracture surfaces of the cyclically loaded specimens revealed fatigue grooves that were clearly observed with a constant pitch corresponding to each degree of cyclic loading (Figure 7). This constant nature of the groove pitch was predetermined by the test conditions — the constant load amplitude at each loading stage. The measured groove pitch was related to the middle section of the fatigue fracture kinetic diagram, and in the entire load range, where fatigue grooves were observed, their pitch corresponded to the average crack rate measured directly on the specimen during the experiment.

Such a correspondence between the microscopic crack rate measured by the groove pitch and the macroscopic crack rate was observed at crack rates exceeding 10^{-7} m/cycle, and the measured groove pitch was in the range of 0.3–2.0 μm. This is in good agreement with many studies (e.g. [10]), where it was shown that the groove pitch correlated well with the macroscopic crack rate at crack rates higher than 10^{-7} m/cycle.

The less regular fatigue grooves observed on the surface of the intergranular corrosion cracks in the welds of the pipes showed a measured groove pitch of 0.4 to 1.0 μm (see Figure 7, *b*), which falls within the above-mentioned groove pitch interval measured on the specimens. This correspondence can be seen as evidence that the cyclic stress component in the pipe affects the growth of a corrosion crack, i.e., the superposition of stress corrosion cracking and fatigue crack growth processes. In other words, we observe the propagation of cracks by the corrosion fatigue mechanism.

FEATURES OF INTERGRANULAR CORROSION CRACKS PROPAGATION

According to the studies carried out on damaged circumferential welds cut out from the pipelines of Unit No. 3 (pipelines of the 1st circuit with an outer diameter of 325 mm and a wall thickness of 16 mm), intergranular corrosion cracks initiate near the root weld on the inner wall of the pipe and propagate, as a rule, in the HAZ along the weld fusion line. In some places, crack initiation are local stress concentrators caused either by metal shrinkage during root weld cooling or by rough machining marks on the pipe's inner surface during welding. A large number of such concentrators on the inner part of the weld and in the near-weld zone leads to the initiation of several cracks. These cracks, which have several nuclei located in different parallel sections of the pipe, often merge into a single crack during propagation. As the moments of initiation of these cracks do not coincide in time, some cracks are ahead of other, which, when merging into a common main crack, leads to its twisting front. The appearance of the surface of one of such cracks is shown in Figure 8, where seven adjacent final fractured templates cut out from a damaged weld are shown.

Each opposite half of the template contains the response surface of the same corrosion crack (of dark colour, facing outward in the image) and the surface of the final crack (of light colour, facing inward), resulting from the mechanical fracture of the templates during their bending.

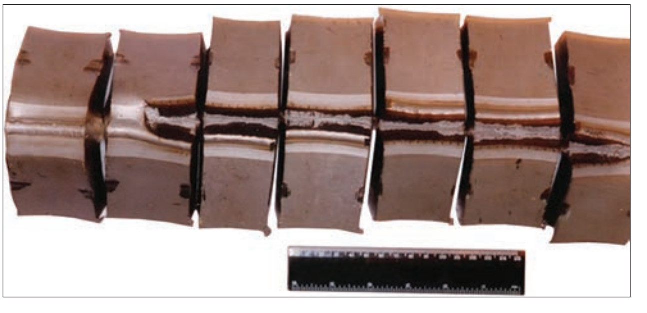

Figure 8. Appearance of a surface crack on the fractured templates

The surfaces of corrosion cracks are covered with a thick layer of corrosion deposits that are dark brown in colour and have significant radioactivity. When studying the growth characteristics of corrosion cracks, it was observed that the choice of the growth trajectory by a crack is largely determined by the place of its initiation, which, in turn, depends on the efficiency (i.e., the sharpness) of the local stress concentrator. Therefore, at the damaged welded joints cut out from pipes, both cracks propagating along the HAZ near the fusion line and (less frequently) cracks growing along the weld metal were observed. To take these features into account, it is necessary, firstly, to determine the strength of the weld metal, and secondly, to determine the limit fracture load of the weld section that remained unaffected by a crack.

CONCLUSIONS

1. Metallographic and fractographic studies of the welded joints of the pipelines of Power Unit No. 3 of the Chernobyl NPP revealed intergranular (with crack growth in the HAZ) and intragranular (with crack growth along the weld metal) fracture. Significant corrosion damage with typical crack branching was observed in both cases.

2. Additional fractographic studies of the surfaces of corrosion fracture of welds confirmed the presence of signs of cyclic loads (fatigue grooves) on a significant fracture area.

3. As a result of comprehensive metallographic, fractographic and micro-X-ray spectral studies, a set of measures was developed to solve the problem of stress corrosion cracking in austenitic steels.

4. In the event of a probable IGC propagation, monitoring the formation and propagation of cracks becomes particularly important for the reliable operation of power equipment. It is especially important to be able to measure the geometric characteristics of cracks, which significantly expands the capabilities of temporary and short-term measures to maintain operational reliability. Therefore, the development and optimization of non-destructive testing methods for welded joints prone to IGC is an urgent task.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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