GROWTH OF CORROSION CRACKS IN STRUCTURAL STEEL 10GN2MFA

V.I. MAKHNENKO[1], **L.I. MARKASHOVA**[1], **O.V. MAKHNENKO**[1], **E.N. BERDNIKOVA**[1], **V.M. SHEKERA**[1] and **A.S. ZUBCHENKO**[2]

[1]E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

[2]«Hydropress», Podolsk, Russia

Relationship between corrosion crack growth rate and stress intensity factor, based on the static corrosion crack resistance diagram, is described. The main working hypothesis on the discrete nature of crack growth in structural steel is confirmed.

Keywords: *welded structures, NPP steam generator, static corrosion crack resistance diagram, structural steel, corrosion cracks, electron microscopy, stress intensity factor, hydrogen embrittlement*

Corrosion cracks are among the most dangerous defects formed in modern durable steel structures. In a number of cases the process of initiation and formation of such defects is hard to determine. Therefore, duration of this process of formation of corrosion cracks may substantially change with time, depending on rather small changes in specific factors.

Under these conditions, of high importance is to timely detect the formed corrosion crack and determine the kinetics of its growth with time during operation of a corresponding structure.

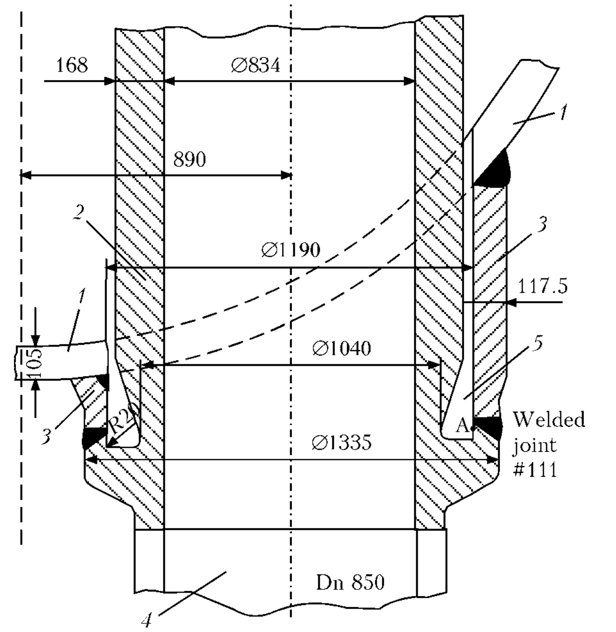

Figure 1. Schematic of the assembly of joining collector to steam generator casing by using branch pipe: *1* — steam generator casing; *2* — collector; *3* — branch pipe; *4* — main circulation piping; *5* — pocket

Very often the latter is crucial and requires accumulation and generalisation of the corresponding experimental data. So, the present study is dedicated particularly to this issue.

Welded joint 111 (Figure 1) in steam generators PG-1000 of modern power units of water-moderated water cooled reactor WWER-1000 considered in this study involves a problem in this respect, as each of units of this NPP comprises four steam generators. 13 such units at 4 NPPs with a service life of 8 to 28 years are in operation now in Ukraine.

The first defects in welded joints 111 were detected in Ukraine in 2003 at the South-Ukrainian NPP. Before that, such cracks in joints 111 were detected at the Novovoronezhskaya and Kalininskaya NPPs in Russia, whish had been in operation for about 20 years. The first detected cracks were mainly longitudinal, i.e. located along the weld, and of rather big sizes both on the circumference and in depth [1], which caused difficulties in detecting them by the non-destructive test methods. The special ultrasonic testing procedure was developed for these purposes [2], which allowed revealing such defects at the early stages of their formation. As the procedure for repair of these defects detected at the early stage of their formation is time-consuming and requires shutdown of the entire unit, the necessity arose for predictive estimates of safe service life of a steam generator with detected crack-like defects in welded joints 111 between both hot (joint 111-1) and cold (joint 111-2) collector and branch pipes of the steam generator casing (see Figure 1).

These predictions are based on the knowledge of the static corrosion crack resistance diagram (SCCRD) (Figure 2). Such diagrams are developed for specific materials (steels) and aggressive environments depending on force factor K_I, i.e. the stress intensity factor for normal tear cracks. SCCRD (see Figure 2) consists of three zones [3]. In zone *I* ($0 < K_I < K_{ISCC}$), where corrosion growth is based on the mechanism of anodic dissolution, the role of the force factor is not high. In zone *II* ($K_{ISCC} < K_I < K_{IC}$), i.e. the zone of hydrogen embrittlement, the rate of growth of a corrosion crack is much higher. The upper bound of this zone, $K_I = K_{IC}$, corresponds to zone *III*, where the crack grows spontaneously.

So far, no sufficiently reliable SCCRD describing the $v = f(K_I)$ growth rate are available for welded joints 111 of high-strength low-alloy steel 10GN2MFA, as composition of the aggressive environment in pocket *5* on joints 111 depends on the service life of the steam generator. At the initial stage of operation, this is a feed water of the second loop at a temperature of about 300 °C and pressure of 6.4 MPa. In such an environment, steel 10G2NMFA used to make steam generator casing *1*, cold and hot collectors *2* and branch pipe *3* (see Figure 1) is almost insensitive to corrosion cracking. However, in long-time operation, owing to the stagnant phenomena taking place in pocket *5*, the composition of the environment in contact with the surface of one-sided welded joints changes. Conditions are created for pitting multicentric surface corrosion to occur along the circumferential weld, which then transforms to stage *I* of formation of a corrosion crack (see Figure 2). It is likely that the uncontrollable surface state in the pocket in a zone of the one-sided weld exerts a significant effect on the time of transition from pitting corrosion to formation of the corrosion crack. Moreover, it is highly probable that the intermediate state here is formation of a groove corrosion defect along the weld, from which the circumferential crack is then formed.

Improvement of thoroughness of control of the zone of welded joints 111 at NPPs in annual fixed-schedule maintenance (FSM) provides early detection of the defects under consideration. However, the predictive estimates of their behaviour turn out to be too conservative, this being associated with conservatism of the used approximate data on the rate of growth of crack sizes $v = f(K_I)$.

At the absence of appropriate SCCRDs, predictions were made by using literature data for similar casing steels and similar service conditions [4], which were in good agreement with calculated rates $v = f(K_I)$ obtained in solving the inverse problem by the results of measurements at the South-Ukrainian NPP in 2003, according to which [1]

$$v = 0 \text{ at } K_I < K_{ISCC},$$
$$v \cong 44 \text{ mm/year at } K_I > K_{ISCC},$$
$$K_{ISCC} \approx 10\text{–}20 \text{ MPa·m}^{1/2}.$$

This approximation for SCCRD provides sufficiently good description of stage *II* (see Figure 2) at defect depths of over 30–40 mm, whereas at a depth of less than 25 mm it turns out to be rather conservative.

Substantial disagreement of the prediction data with the control measurement results obtained at further FSM, e.g. the results of growth of crack-like defects detected in 2009 in welded joints 111-2 at steam generators of unit 3 of the Rivnenska NPP, whose dimensions *a* and 2*c* remained almost unchanged in testing during further FSM in 2010 and 2011, cast doubt on applicability of the mechanism of growth of such defects (see Figure 2, stage *II*) for steel 10GN2MFA.

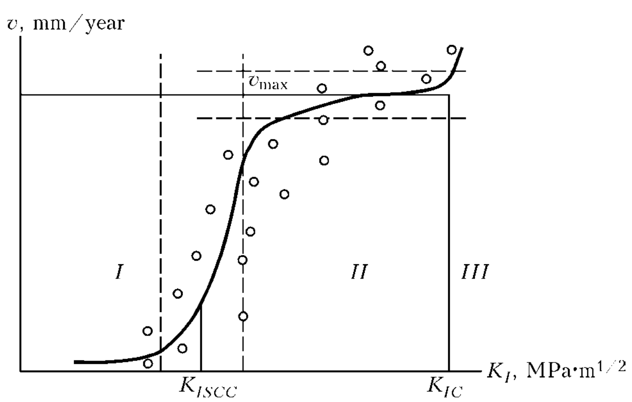

Figure 2. Static corrosion crack resistance diagram (see designations in the text)

Figure 3. Appearance of the testing machine for determination of SCCRD parameters

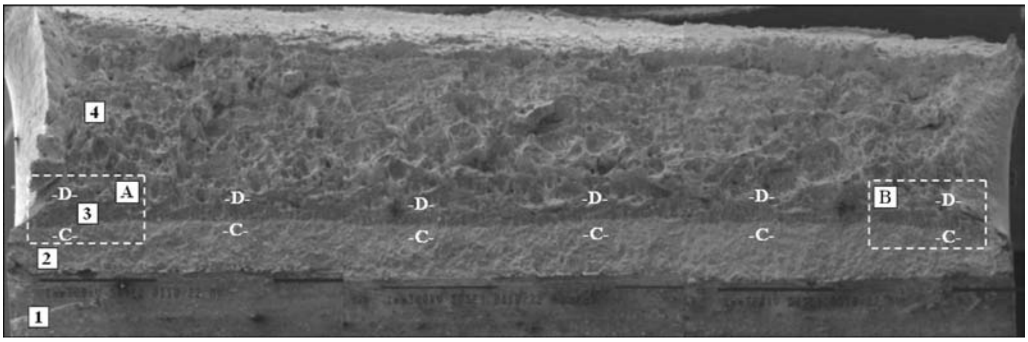

Figure 4. Panoramic view of fracture in specimen 1 (see designations in the text)

In this connection, the experimental study was carried out on specimens of steel 10GN2MFA of the following chemical composition, wt.%: 0.11 C, 0.28 Si, 0.89 Mn, 0.19 Cr, 2.1 Ni, 0.44 Mo, 0.04 V, 0.11 Cu.

The Charpy type specimens with a cross section of 10 × 10 mm, sharp notch and a preliminarily grown fatigue crack were loaded by three-point bending using the testing machine (Figure 3) described in studies [5–7]. The tests were carried out in 3 % solution of NaCl at a temperature of 35 °C and a load corresponding to K_I = = 25 MPa·m$^{1/2}$. The load was determined by dynamometer DOSM3-3. The machine was fitted with an acoustic emission sensor to fix the crack growth surges by using instrument AEC-USB-1.

Two specimens were tested for 778 (1) and 601 h (2). After the tests, the specimens were completely fractured and their surfaces were cleaned from the corrosion deposit, after which a panoramic view of the fracture surfaces was obtained (Figure 4) by using «Philips» scanning electron microscope SEM-515 equipped with the «Link» energy-dispersive spectrometers.

Four zones can be clearly seen in Figure 4. Zone 1 corresponds to the Charpy specimen notch 2 mm deep, zone 2 is a preliminarily grown fatigue crack, zone 3 is a corrosion crack between

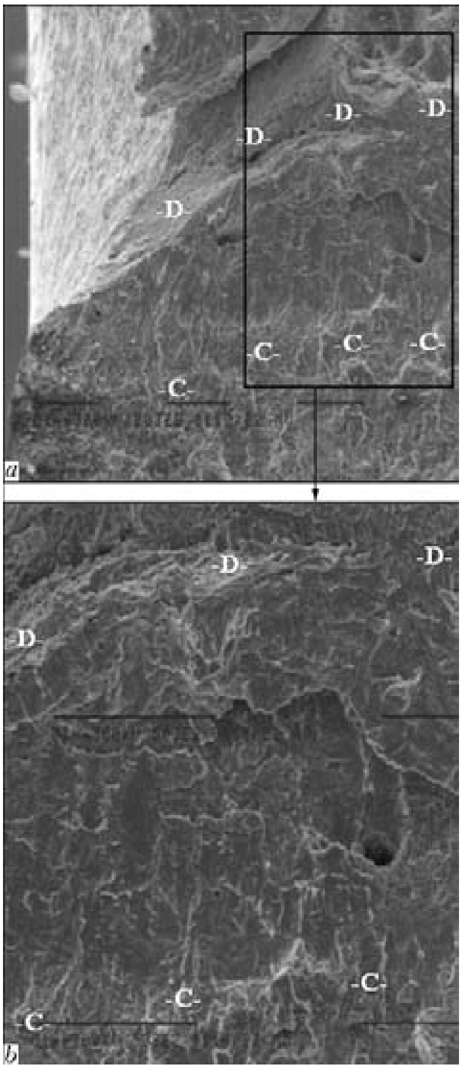

Figure 5. Fragments of fractographic pattern and zone A (see Figure 4): *a* — ×203; *b* — ×503

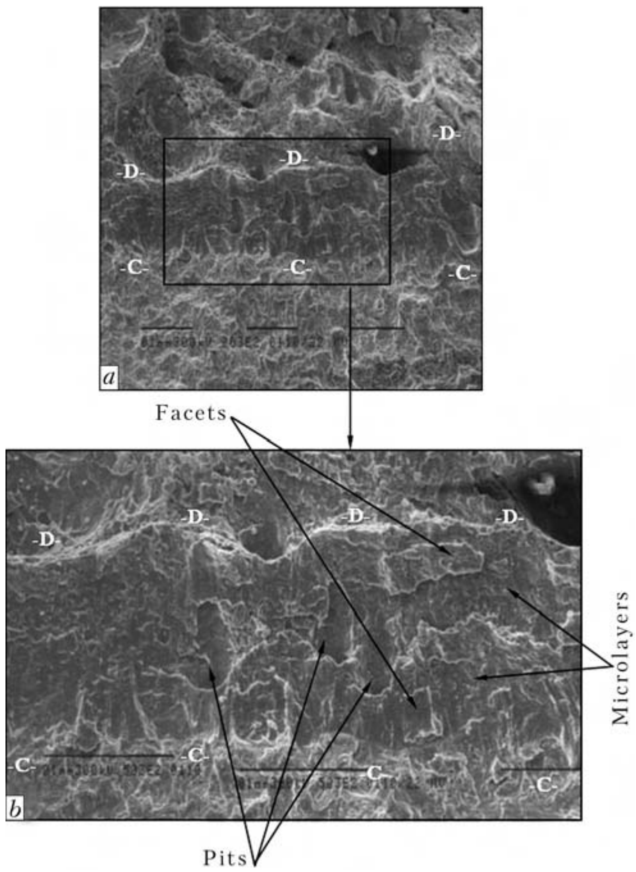

Figure 6. Fragments of fractographic pattern and zone B (see Figure 5): *a*, *b* — same as in Figure 5

lines C–C–C and D–D–D, and zone 4 is a complete fracture zone.

Width of the corrosion crack growth, i.e. the Δl value between lines C–C–C and D–D–D determined by using the scanning electron microscope in 16 regions with a pitch of 500–600 μm, was 200–350 μm. For specimen 1, Δl = 229 μm in region 1; 260 μm in region 2; 250 μm in region 3; 240 μm in region 4; 250 μm in regions 5 and 6, 280 μm in region 7; 300 μm in region 8; 270 μm in region 9; 230 μm in region 10; 240 μm in region 11; 260 μm in region 12; 300 μm in region 13; 350 μm in region 14, and 200 μm in regions 15 and 16.

In addition, the measurements were made on side surfaces of the specimens by using measurement microscope UIM-21 with an accuracy of not less than ±2 μm. In this case the width of the crack growth was 284 and 207 μm, this corresponding to a crack growth of 3.20 and 3.01 mm/year.

Further detailed studies of fractographic patterns of fracture were carried out in regions A and B (see Figure 4) close to side surfaces of the specimens. Corresponding data at different magnifications are shown in Figure 5, and those for region B — in Figure 6.

As shown by fractographic examinations, the corrosion crack in zone *II* of SCCRD of hydrogen embrittlement grows in jumps, the frequency of which corresponds to the fixed acoustic emission signals. However, it grows not simultaneously over the entire crack front, but in individual spots moving along the front in a chaotic manner, though forming the growth layers about 30–40 μm thick. An acoustic emission signal accompanies a jump of formation of the said crack spot, which can be regarded as a sign of stage II of hydrogen embrittlement in Figure 2.

CONCLUSIONS

1. Steel 10GN2MFA used to make the steam generator, collector and piping has a sufficiently high corrosion resistance in contact with the second loop environment, this being evidenced by an unptotected surface of the steam generator casing. However, under the high temperature and pressure conditions, which take place inside the collector and piping, the walls of the latter are protected by corrosion-resistant cladding of austenitic steel.

2. In pockets, where the joint between the collector and branch pipe Dn 1200 is situated, the stagnant phenomena result in formation of a very aggressive environment (at least compared to feed water inside the steam generator), this leading to the corrosion process occurring in the region of weld 111.

3. Depending on the aggressiveness of the environment in the pockets, as well as on the state of the contact surface, formation of the corrosion crack is preceded by the process of pitting corrosion of a differing duration and the probability of formation of a corrosion groove-like defect.

4. Conservatism of the predictive estimates of growth of a detected crack-like defect at the early stage is associated with multicentricity of the process, where formation of the crack along the length of the defect occurs non-simultaneously.

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