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Welded Joints Corrosion and Mechanical Strength of Piping for Light Water Reactors

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ABSTRACT

In the process of operation of RBMK reactors the damages were taking place on welded pipings, produced from stainless austenitic steels. The inspection of damaged sections in piping has shown that in most cases defects are of corrosion character. The paper considers in details the reasons for damages appearance and their development for welded piping joints ∅325x16 mm, which produced from austenitic stainless steel 08X18H10T. Crack-like damages were revealed near welded joints in downcomes tubes, manufactured from stabilized austenitic steel after its operation $(60\text{-}120)\times10^3$ hours. The fracture surface of these cracks is similar to that of the intergranular corrosion fracture.

INTRODUCTION

Austenitic stainless Cr-Ni steels of the type 18-10 are widely used in power engineering because of their high resistance to general corrosion. The rate of general corrosion for these steels does not exceed 0.01 g/m^2 h under conditions of boiling reactor operation. This provided a reliable stable operation of reactors, because there was no problem of precipitation and removing of metal oxides from heat exchanging surfaces of reactor channels.

For a number of Russian NPPs numerous cases of crack-like damages were revealed near welded joints in pipings (downcomers ∅325x16 mm), manufactured from the stabilized austenitic steel 08X18H10T after their operation for 50 000-100 000 h at various units. As was determined by X-ray inspection, ultrasonic testing and metallographic examination, these cracks initiated from concentrators at the inner surface of tubes in the vicinity of the fusion line of the weld root with base metal. Cracks propagated along the heat affected zone (HAZ) within the narrow zone (0.3-1.0 mm) near the weld fusion line (Fig.1). Sometimes a crack started in a weld, but here did not further develop and again returned to the HAZ. The fracture surface of these cracks is similar to that of the intergranular corrosion fracture (further defined as intergranular stress corrosion cracking - IGSCC). The same fracture modes were observed in welded joints of instabilized austenitic steels applied at NPPs in western countries [1-3] and resulted in their replacement. The IGSCC of welded joints was found both in steels without stabilizing additions of titanium and niobium and in steels with these stabilizing additions. In the latter case IGSCC can be revealed only after a prolonged operation time.

The aim of the present research is to clarify the nature of IGSCC and to develop recommendation for the prevention of such failures. The report is the review of investigations performed at the institute [4-8].

1.OPERATING CONDITIONS OF DOWNCOMERS

1.1 Water Chemistry Regime

Analysis of chemistry water data from Ignalina and Leningrad NPP has shown that the controllable parameters of water quality (conductivity, impurity contents, pH) met the requirements of water chemistry specifications for water cooled reactors.The oxygen contents in the coolant of these boiling reactors is not regulated. Measuring of oxygen concentration in circulating water of these plants taken in various periods of operation has shown that it was within the limits from 0.05 to 0.19 ppm by steady-state operating conditions and could reach 8 ppm for downtime and input of blocks in operation (Table1) [6].

Water chemistry specifications for water cooled RBMK reactors Table 1

Parameters	Normative value	The facts			
		Leningrad NPP		Ignalina NPP	
		Steady-state operating conditions	Downtime	Steady-state operating conditions	Downtime
Conductivity, μS/cm	≤1.0	0.17-0.31		0.08-0.19	
Cl^-, ppm	≤0.07	0.006-0.03		0.003-0.01	
Fe^+, ppm	0.05	0.015-0.042		0.002-0.04	
Cu^+, ppm	0.02	0.001-0.002		0.002-0.013	
PH (room temperature)	6.5-8.0	6.8-7.5		6.6-7.4	
Oxygen, ppm	-	up 0.05	up 8.0	up 0.19	up 0.34

1.2 Level of Acting Stresses

In the process of operation, stresses from internal pressure supports weight as well as forces from the self-compensation of temperature transport of tubes, drum-separator and suction manifold are superimposed on residual stresses of piping stated (post-welding heat treatment was not carried out)..

It were performed the numerical investigations of stress-strain state of downcomers butt joints after welding and during operation [6]. According to the obtained results the level of acting stresses at the inner surface along the fusion line near the weld root are tensile and reaches the maximum at a depth of 2 mm from the inner surface for all cases considered (Fig.2). This value exceeds yield stress of material. Beginning with 11 mm tube wall thickness the acting stress transforms into compressive ones.

1.3 Mechanical Properties and Microstructure of Downcomers Metal

The mechanical properties of tubes metal must meet the definite requirements of yield strength, reduction of area and grain number. The yield strength at the elevated temperature 350°C - 170 MPa, ultimate tensile strength at the same temperature -350MPa, the reduction of area at room temperature - 37%. The grain number must be not more than 4. All tubes should be heat treated and tested on resistance to intercrystalline corrosion (ICC) according to GOST 6032-89 [9] with a provocating heating. Tubes are delivered, having electrochemical polished surface or machined inner surface with the surface finish 6.3 μm. Having been bent, tubes (Ø325x16 mm) were subjected to heat treatment.

Two welding methods were used for the production of these pipe-lines (MAW and TIG). Electric arc manual welding was performed with EA-400/10Y or EA-400/10T electrodes (OST 5.9370-81). Manual welding and automatic non-consumable electrode arc welding (TIG) were performed with Sv-04X19H11M3 wire (GOST 2246-70).

Mechanical properties of materials after a prolonged operation (metal of Leningrad NPP downcomers welded joints) and in as-welded conditions were determined at temperatures 20, 190 and 290°C [8]. It is established that mechanical properties of investigated materials (without cracks) meet the requirements for the specified structures. The strength characteristics ($\sigma_{0.2}$,σ_{US}) of both the base metal and welded joint raise by 1.5-2 times after 120 000 h of the operation, the relative elongation and reduction of area remain at the same level. The fracture mode of specimens fabricated from welded joints was ductile with the formation of a neck in the HAZ.

The microstructure of the HAZ metal of downcomers welded on the identical plant technology was investigated in as-produced condition and after operation during 80 000 h. In the last variant samples were made from damaged tube detected at Ignalina NPP.

The metal of tubes had the austenitic structure with polyhedral grains having a 3-60 microns size and a set of twins of sliding after welding performed on standard technology. The steel is contaminated with nonmetallic inclusions of titanium carbonitrides in the form of isolated inclusions or extended chains. There are isolations of ferritic phase. A layer of coarse granular metal (the grain size up to 175 micron) is formed near a weld root along the fusion line. It was established the chromium carbides precipitation at grain boundaries by methods of metallographic and X-ray spectrum analysis.

The sensitization degree was determined after electrolytic etching in a standard water solution of the oxalic acid as the relation of boundaries' length by a higher etching against the summary length of boundaries. The etching time was identical of all samples.

The sensitization degree of steel did not exceed 10 -20 % in a zone of coarse granular metal. Metal located above the weld root was sensitized much less.

The grain size of the HAZ metal after prolonged operation did not practically differ from that of the grain size in as-produced condition, however the sensitization degree sharply grew (Fig.3) [6]. The sensitization degree on the internal surface at the weld root was 60 % and its maximum size (80 %) was marked at the distance of 1 mm from internal surface. The crack stopped in the area of fine granular metal (≈5 mm from the weld root) and within it the sensitization degree fell up to zero. Metal of the HAZ in the vicinity of the weld toe was not practically sensitized.

Piping welded joints after operation did not exhibit tendency to ICC according AM GOST 6032-89 [9].

2. REASONS AND NATURE OF DOWNCOMERS DAMAGES

The defects represent intergranular cracks located along the weld root on the HAZ at the distance up to 0.5 mm from the fusion line. The cracks are in the zone of coarse granular sensibilized metal with the sensibilization degree 40-80 %. Metal sensibilization develops in two stages. The first stage is a "initial" sensibilization which is characterized by chromium carbides precipitation. The second stage is carbides growth during operation. The cracks arrest in the area of fine granular metal, the sensibilization degree of which is small. At the same time the HAZ metal does not display the susceptibility to ICC.

All features mentioned above are associated with the phenomenon known as IGSCC the necessary conditions for its occurrence are [10-12]:
- a high sensitization degree of grain boundaries;
- presence of dissolved oxygen in amount of 0.2-8 ppm in high-temperature water;
- a high level of acting tensile stresses on the fusion line.

These conditions are observed during the operation of downcomers. In this way the nature of defects formation is IGSCC.

It was supposed that short-term heating in the range of dangerous temperatures during welding should not result in sensitization of stabilized austenitic steel. However the HAZ metal is heated up to temperatures close to the melting temperature by welding. It results in a partial solution of titanium carbides, fixation of carbon in solid solution, chromium carbides formation in the process of cooling after welding and repeated heating within a temperature range 500-650°C. Repeated heating takes place by producing usual welding beads.

Grain boundary sensitization occurs by welding (initial) and develops at low temperature (290°C) in the process of operation due to chromium carbides growth . Chromium diffuses to growing particles of carbides on grains' boundaries and on dislocations on them at low temperature sensitization [12]. Carbides grow and form chains. It results in the formation of extremely thin neighbouring zones having thickness less than 4 nm depleted in chromium [12]. A final sensitization depends on the initial one.

3. INFLUENCE OF WELDING TECHNOLOGY ON SENSITIZATION DEGREE OF AUSTENITIC WELDED JOINTS

The sensitization degree of HAZ metal during operation is determined by an initial level caused by welding - the greater the initial sensitization the more rapidly its level is achieved by which IGSCC is begining. It is necessary to decrease the duration of metal stay within the range of dangerous temperatures in the process of welding for the reduction of sensitization degree. It is defined by the welding technology.

3.1 Effect of Welding Modes

Welding modes can influence singnificantly the maximum temperatures and heating time of close to weld zone. The reduction of relative energy of welding arc (heat supply) is achieved by welding current and arc voltage decrease and also by welding speed increase.
However, an excessive limitation of welding modes is inadmissible because of the instability of welding arc combustion process and the possibility of production defects formation. Therefore, the welding current is specified by the normative documentation and depends on wire electrode diameter; arc voltage varies inconsiderably by manual welding. Welding speed should be limited at the expense of narrow beads production.

Thus, the heat supply reduction means of the variation of welding conditions is quite limited and consequently it comes to the meeting of normative documentation requirements. As the experimental results showed, in case of welding in increased current regimes, the grain growth zone width and spreading along the weldment height increased and this zone can be sensibilized completely.

3.2 Effect of Welded Joints Types

One-sided welded joints of tubes (without backing rings) were fabricated using glass-like edge preparation; the welding of the first pass was carried out by argon arc method with non-consumable electrode and without filling wire. At present in case of repair V-type edge preparation is used. By this, tubes are assembled with a 1.0-2.0 mm clearance and the first pass is performed with filling wire. In our opinion, the advantage of this technology is that electric arc heat is consumed for the melting-down of not only edges but also welding wire. The wire application permits to provide the ferritic phase presence in deposited metal and exclude the possibility of hot crack generation. Proceeding from geometrical dimensions the height of first three to six beads by filling of V-type edge preparation is greater in comparison with the U-type preparation and it reduces the sensibilization of close to weld root zone depending on subsequent beads. The mechanical treatment of tube edges is also easier. Therefore, in future such type of welded joint can be used not only under assembly but also plant conditions. However, the standard metallographical studies of specimens show that the application of the stated above edge preparation does not exclude a possibility of sensibilization in close to weld root zone.

3.3 Effect of Welding Method

The piping welding was carried out by two methods – manual TIG and a combined method (root – TIG, filling – covered electrodes). Sometimes automatic TIG is used. The comparison of manual TIG with covered electrode welding shows that with the use of welding wire and electrodes having the same diameter these welding methods are equivalent in heat supply, but differ in the deposition coefficient:

$$\alpha_{cl}=Q_{cl}/I_{w.c.}\tau \qquad (1)$$

where Q_{cl} is the cladded metal mass, $I_{w.c.}$ is the welding current, τ is the welding duration.

By covered electrode welding α_{cl}=12 g/A h and it is greater by 2-4 times than that by manual TIG. In this connection with the values of welding current covered electrode welding provides a greater amount of deposited metal and a smaller number of beads and, consequently, a lower heat influence on close to weld zone. By submerged arc welding the coefficient α_{cl}=15 g/A h. However, this welding method is characterized by a higher welding regime ($I_{w.c.}$ >300 A) and it can induce sensibilization of close to weld zone directly by the production of each bead. The semi-automatic and automatic MIG having α_{cl}=16 g/A h and permitting to increase welding output with minimum heat putting are also perspective.

3.4 Effect of Metal Cooling After Each Pass.

In order to increase the resistance to ICC by the production of multi-pass welds in austenitic steels, it is necessary to cool deposited metal after each pass to a temperature not higher than 100°C. Experiments show that specimens welding without cooling (with «overheating») induces an increased sensibilization of close to weld zone, especially weld root.

A forced cooling of specimens from inner and outer surface of tubes with water influences favourably. The structure close to weld zone was not established and grain growth was observed only by the production of the first pass, the welding of which was carried out without water cooling.

However, the sensibilization degree depends not only on welding technology but also on 08X18H10T steel tendency to the formation of chromium carbides. Thus, in the case of the presence of coarse carbides precipitation on grain boundaries a forced cooling with water and welding in minimum regimes ($I_{w.c.}$=60-80 A) does not exclude sensibilization and grain growth (close to weld zone) of specimens welded by TIG. Therefore the corrosion resistance of such welded joints to ICC corrosion can be increased by one-pass cladding on the inner surface of 30-40 mm wide tubes from ends, using corrosion resistant welding materials (the type EA-898/21B electrodes and Sv-04X20H10G2B wire).

The investigations of experimental welded joints, fabricated using various technologies confirmed the fact that by reducing heat input in the process of welding it is possible to decrease significantly the degree of "initial" and final sensibilization. The sensibilization degree obtained on factory technology (manual TIG, 8 beads) is equal to 13-20 %, on recommended repair technology (13 beads) – 3-9 %. In case of welding with water cooling after the fabrication of three beads or with the use of austenization at 1050°C for 1 h the initial sensitization was not observed. The welding process with superheating, with welding current 300 A, with cooling of each bead causes the initial sensitization 30-40 %, i.e. such sensitization by which IGSCC can be develop immediately after welding.

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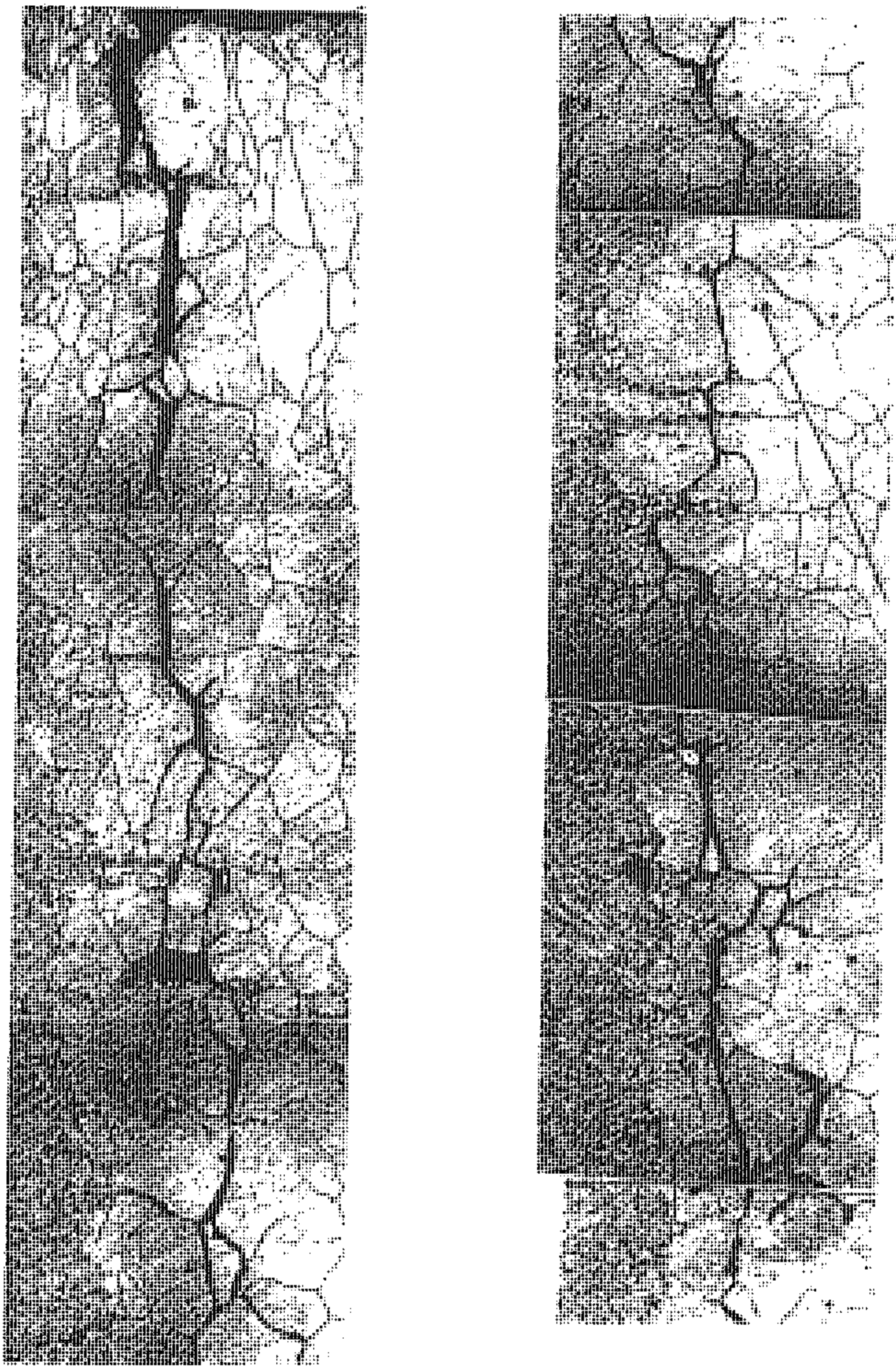


Fig.1. IGSCC crack view on welded joint Ø325x16 mm downcomers.

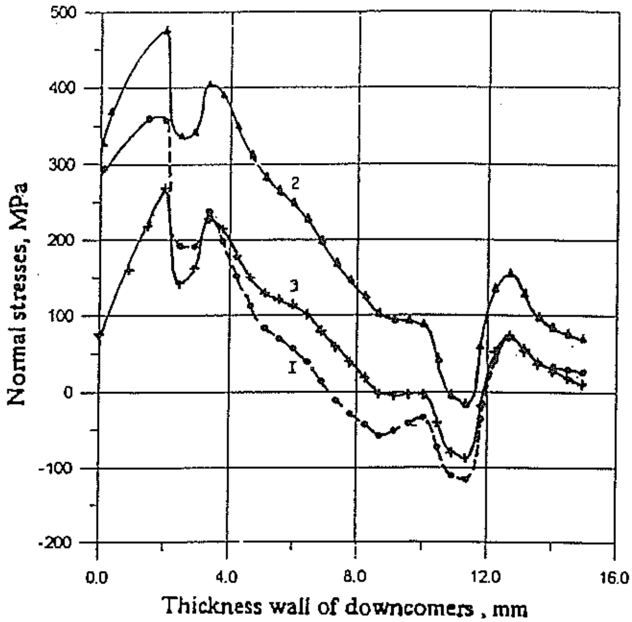
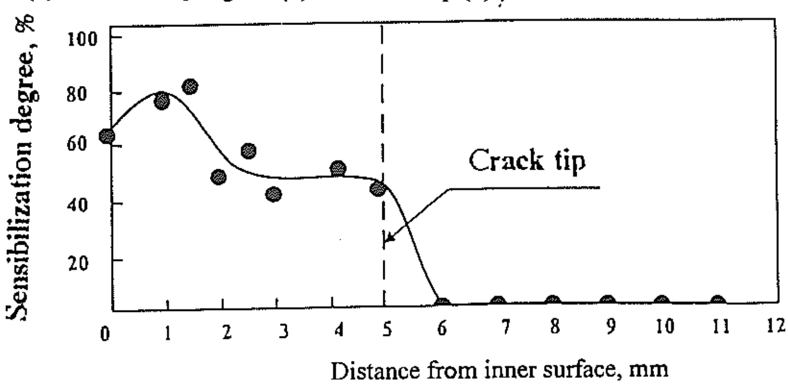


Fig.2. Distribution of normal stress component on fusion line in as-welded condition (1), in stationary regime (2) and after stop (3).



$$\text{Sensibilization degree} = \frac{L_{\text{boundary of high ability to etching}}}{L_{\text{general boundary}}}$$

Fig.3. Material sensibilization degree close to weld zone along crack.