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# LOW-TEMPERATURE CORROSION DAMAGE AND REPAIR OF BOILER BOTTOM PANEL TUBES

# NISKO-TEMPERATURNA KOROZIONA OŠTEĆENJA CEVI DONJE PLOČE KOTLA I NJIHOVA REPARACIJA

Originalni naučni rad / Original scientific paper
UDK /UDC: 620.193:621.184
621.792.75:621.184
Rad primljen / Paper received: 12.10.2017

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**Keywords**
- hot water boiler bottom panel
- low-temperature corrosion
- repair welding

*Abstract*

*The method used for repairing of the bottom panel of hot water boiler of 30 MW power, manufactured by Remming (a part of the 'Valjevo' Heating Plant) is presented in this paper along with the reasons why damage has occurred. The damage appeared on bottom panel as a consequence of service conditions to which the boiler was subjected. It has resulted in the thinning of tube walls in the bottom panel. Low-temperature has been determined as the cause of the tube damage, i.e. due to the presence of sulphuric acid. For the purpose of damage analysis and proper selection of the repair welding technology, the first tube wall measurements were performed in the boiler bottom panel. Upon determining the necessary repairs, and due to damages not originally included, the wall thickness tests are repeated and microstructural analysis by metallographic replica testing (for one tube) is performed. No major microstructural defects typically caused by exploitation conditions have been detected on the examined screen tube surface. The repair welding procedure which involved replacing of the bottom panel is also shown, along with suggestions for further damage prevention. Repair welding is performed using MAG welding procedure, combined with gas welding.*

**Ključne reči**
- donja ploča vrelovodnog kotla
- nisko-temperaturna korozija
- navarivanje

*Izvod*

*U ovom radu je prikazana metoda reparacije donje ploče kotla za vrelu vodu, snage 30 MW, proizvedenog od strane Remming (u sklopu toplane „Valjevo"), zajedno sa razlozima zbog kojih dolazi do oštećenja. Oštećenja su se javila na donjoj ploči kao posledica radnih uslova kojima je kotao izložen, i usled kojih je došlo da stanjenja zida donje ploče. Utvrđeno je da su oštećenja izazvana nisko-temperaturnom korozijom, tj. usled prisustva sumporne kiseline. U cilju analize oštećenja i izbora odgovarajuće tehnologije navarivanja, prvo je izvršeno merenje zidova cevi donje ploče kotla. Nakon određivanja obima neophodne reparacije usled oštećenja koja nisu prvobitno obuhvaćena, ponovljeno je ispitivanje debljine zidova, uz analizu mikrostrukture primenom metode replike (za jednu cev). Na ispitivanoj površini cevi donje ploče nisu uočene nikakve mikrostrukturne greške koje se inače javljaju u radnim uslovima. Postupak navarivanja, koji je obuhvatao zamenu donjih ploča je takođe prikazan, uz predloge kako izbeći dalja oštećenja. Navarivanje je izvedeno MAG postupkom, u kombinaciji sa gasnim zavarivanjem. Pored toga, u radu su prikazani i zahtevi vezani za uspešno izvođenje tehnologije zavarivanja.*

## INTRODUCTION

Metal corrosion is caused by the electro-chemical influence of external factors on the metal's surface. Corrosion manifests itself through different types of physical and chemical processes that take place at different sides of the component subjected to exploitation conditions, /1-5/. Corrosion can be classified as high-temperature and low-temperature, as well as local and surface. Low-temperature corrosion is the most commonly encountered kind and can lead to significant damages in boiler components working at lower temperatures, reducing their availability which requires undertaking certain measures for prevention, /6-8/. During the combustion of sulphur, sulphur dioxide is formed. Under the conditions that are present in the firebox, a portion of the sulphur-dioxide binds with the oxygen, producing the sulphur-trioxide in an exothermal reaction given by Eq.(1),

$$2SO_2 + O_2 = 2SO_3 \qquad (1)$$

It is known that at elevated temperatures ($t > 1000$ °C), atomic oxygen reacts with sulphur-dioxide. Sulphur-trioxide can form at lower temperatures ($t < 400$ °C) in the presence of catalysts. Due to the separation of moisture from the gases on boiler membrane walls, sulphur-trioxide binds with water producing the so-called sulphuric acid, $H_2SO_4$, which causes low-temperature corrosion, thus damaging the tube walls. The chemical relation showing the formation of sulphuric acid is:

$$SO_3 + H_2O = H_2SO_4 \qquad (2)$$

In the case when the sulphuric acid remains in the boiler, it will not corrode the heating surface. If the tubes located in the firebox are slightly slanted, the sulphuric acid will accumulate. Sulphuric acid has an aggressive effect on the metal, resulting in damages to the parent material. In most cases, sulphuric acid causes the thinning of tube walls, which could lead to catastrophic damage and failure.

Damages of boiler tubes are one of the primary causes of heating plant facilities forced outages in many utilities worldwide, including even in the most advanced countries. This is due to a very complex interconnection of design and history of operation of each particular boiler unit, /5, 9/. Structural integrity of boiler tubes is the major goal in contemporary thermal plant facilities maintenance programs.

'Valjevo' heating plant possesses two hot water boilers which produce 30 MW and 50 MW of power, /10/. The heating plant's task is to generate heat and distribute it to end users. Oil is used as fuel in the boiler heating process. The 30 MW boiler, in question, is subjected to two repairs since 2007, when it was put into service, until 2016. The highest allowed working pressure for this boiler is 16 bar, whereas the maximum test pressure is 33 bar. The boiler volume is 14 100 litres, whereas its highest working temperature is 130°C. Heated surface of the boiler is 656 $m^2$.

The procedure for hot water boiler bottom panel tube inspection is shown in the following section, along with clarifications and procedures used for successful repairs. Microstructural analysis determined that low-temperature corrosion has caused damage to the bottom panel tubes. The heating system in question is direct, with primary temperatures of 130/75°C, and secondary temperatures of 90/70°C. Microstructures of damaged tubes and the results of wall thickness tests are shown in the following text. In addition to the procedure itself and the test results, shown are the requirements that need to be fulfilled for successful repair welding of heat installations, along with the steps for preventing future major damages, including more frequent inspection across shorter time intervals and/or potential reconstruction of the installation.

## INSPECTION, PROBLEM BACKGROUND, AND FIRST UNSUCCESSFUL REPARATION

During typical preparations for the new heating season, visual inspection of all important parts of the hot-water boiler in the 'Valjevo' heating plant are performed (pore reinforcement, safety valves, supply pumps, chemical preparation of water, etc), along with the visual inspection of the boiler structure itself (firebox, eco-packages, burner).

During the visual inspection of the firebox, damages mostly present in the bottom panel are observed. In addition, large edge notches and damages in the connection between membrane strips and tubes are detected (Fig. 1, top), along with occasional damage in the tubes themselves (Fig. 1, bottom).

### *First measurement of tube wall thickness*

For the purpose of determining the extent of damage to the lower floor screen, NDT testing of membrane tube wall thickness is performed by the Welding Institute in Belgrade. Wall thinning due to the effects of sulphuric acid is observed on the screen tube walls (Fig. 2).

The bottom panel of the firebox consists of 35 tubes with membrane strips in between. Tubes are denoted by numbers 1-35, from the right lateral panel to the left. Measurements are performed in three cross-sections. Cross-section I-I is located at a distance of 500 mm from the firebox wall, cross-section II-II is located at a distance of 1400 mm from the front firebox wall, whereas cross-section III-III is at a distance of 2400 mm from the front firebox wall. Measuring is performed in a single point, i.e. on the upper side of the tube. After measuring, it is determined that the most damaged zone includes tubes 7-29 at a distance of approximately 1000 mm from the front screen. Once this part of the floor screen is cut and dismantled, it has been revealed that the damages are more prominent in the connection between the tubes and the membrane sheet, as can be seen in Fig. 2, and that thickness measurements provided unfavourable results. Repeated measuring determined that floor screen damages are greater than initially assumed. The cutting line was moved to almost 3000 mm from the front screen.

Figure 1. Edge notches in the connection between membrane strips and tubes (top); tube damage (bottom).

Figure 2. Zones of the largest damage and wall thinning.

*Initial unsuccessful bottom panel repair*

After the tube wall thickness tests, cutting, i.e. dismantling of the bottom panel is performed according to the new cutting line. Welding preparations were undertaken, and new tubes have been welded. After the original welding, radiography of these new joints is performed. No significant defects were detected. After completing all procedures, the joints are tested using cold water pressure, in the presence of the appointed body. A new problem arose during the tests. One of the tubes that has not been the subject of previous repair has leaked (Fig. 3), which resulted in the need for additional tests and an increased extent of repairs.

After determining the necessity to increase the extent of repairs, wall thickness testing was also extended. Additional measurements were performed, however, this time including the first six tubes (1-6) and the last six tubes (30-35) as well. It was determined that they too were damaged due to exploitation conditions. Measuring is performed in the cross-section at a distance of 1300 mm from the front tube panel, on two measuring locations in all tubes (Fig. 4). The tubes were once again dismantled, but this time the chamotte located near the firebox screen edges was also removed in order to release tubes 1 and 35. The tubes were again cut and subjected to further tests, and later on, to repair welding in order to eliminate the damage. Results of tube wall thickness measurements are shown in Table 1.

Figure 3. Leakage during the pressure test.

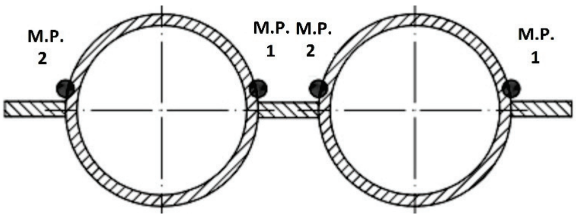


Figure 4. Measuring points (M.P.) in the tubes.

*Microstructural analysis of the damaged tubes*

Microstructural analysis of the fourteenth tube of the bottom panel of the hot-water boiler subjected to the influence of the firebox is performed using the replica test. The tube was in service for 7 years. The metallographic replica are obtained from the outer side of the tube.

Metallographic analysis has determined a ferrite-pearlite type microstructure on the tested location at the surface (Fig. 5a-d) with a significantly reduced share of pearlite micro-constituent. It has also been observed that initial ferrite-pearlite strip structures are present, along with coarse ferrite grains, which is not related to the exploitation period of the tested tube, but rather a consequence of the manufacturing technology used on the tube.

The presence of unallowed microstructural defects that could have resulted from exploiting conditions and previous service life, such as degradation of the pearlite micro-constituent, surface decarbonisation, existence of surface corrosion remnants or intergranular corrosion, etc., have not been detected during the testing of the surface microstructural state of the tube.

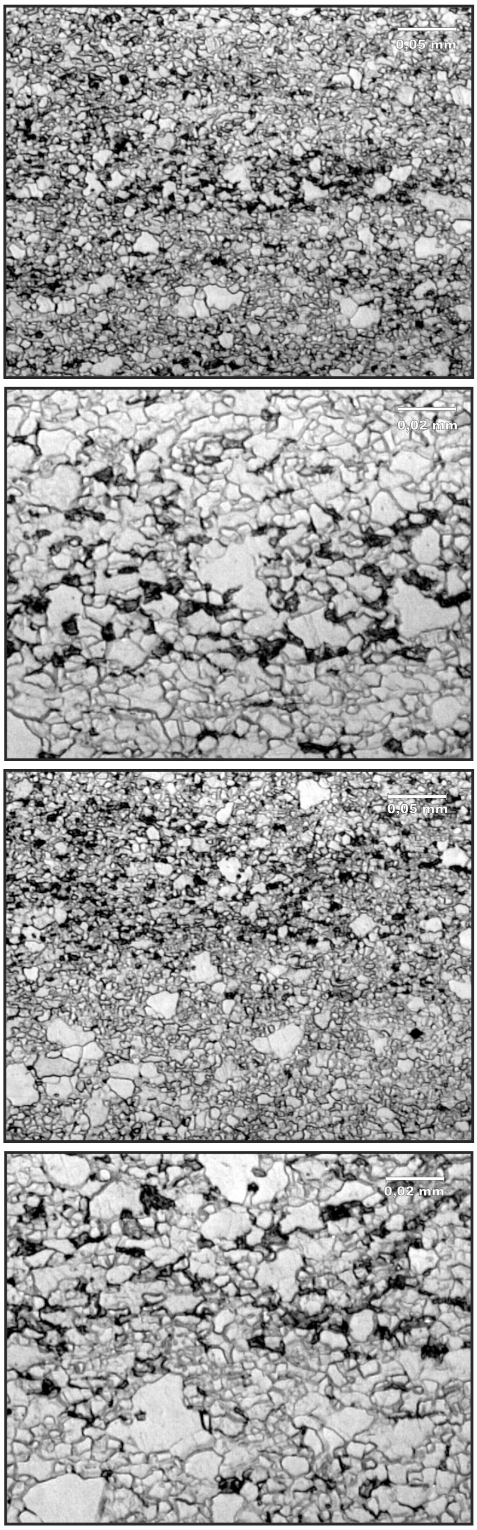


Figure 5. Microstructure of selected tube taken from the Remming hot-water boiler panel.

Table 1. Measured wall thicknesses on the bottom panel tubes, cross section I-I at 1300 mm from the front tube panel.

| Measuring point (MP) | | Value (in mm) | Measuring point (MP) | | Value (in mm) | Measuring point (MP) | | Value (in mm) |
|---|---|---|---|---|---|---|---|---|
| Tube 1 | MP1 | - | Tube 13 | MP1 | 3.2 | Tube 25 | MP1 | 2.3 |
| | MP2 | - | | MP2 | 1.4 | | MP2 | 1.3 |
| Tube 2 | MP1 | - | Tube 14 | MP1 | 2.6 | Tube 26 | MP1 | 1.6 |
| | MP2 | 3.5 | | MP2 | 1.4 | | MP2 | 1.7 |
| Tube 3 | MP1 | 1.7 | Tube 15 | MP1 | 2.2 | Tube 27 | MP1 | 2.0 |
| | MP2 | 3.2 | | MP2 | 1.4 | | MP2 | 1.6 |
| Tube 4 | MP1 | 3.8 | Tube 16 | MP1 | 1.7 | Tube 28 | MP1 | 2.9 |
| | MP2 | 3.2 | | MP2 | 1.5 | | MP2 | 2.6 |
| Tube 5 | MP1 | 3.2 | Tube 17 | MP1 | 2.1 | Tube 29 | MP1 | 3.5 |
| | MP2 | 3.7 | | MP2 | 1.8 | | MP2 | 2.4 |
| Tube 6 | MP1 | 3.7 | Tube 18 | MP1 | 1.3 | Tube 30 | MP1 | 3.7 |
| | MP2 | 3.0 | | MP2 | 1.3 | | MP2 | 1.8 |
| Tube 7 | MP1 | 3.9 | Tube 19 | MP1 | 2.0 | Tube 31 | MP1 | 3.1 |
| | MP2 | 3.2 | | MP2 | 1.9 | | MP2 | 3.0 |
| Tube 8 | MP1 | 3.7 | Tube 20 | MP1 | 2.1 | Tube 32 | MP1 | 2.5 |
| | MP2 | 3.1 | | MP2 | 2.4 | | MP2 | 3.5 |
| Tube 9 | MP1 | 3.7 | Tube 21 | MP1 | 1.7 | Tube 33 | MP1 | 3.0 |
| | MP2 | 2.9 | | MP2 | 2.0 | | MP2 | 1.8 |
| Tube 10 | MP1 | 3.2 | Tube 22 | MP1 | 2.6 | Tube 34 | MP1 | 2.2 |
| | MP2 | 2.2 | | MP2 | 3.1 | | MP2 | - |
| Tube 11 | MP1 | 3.2 | Tube 23 | MP1 | 2.0 | Tube 35 | MP1 | - |
| | MP2 | 1.9 | | MP2 | 1.8 | | MP2 | - |
| Tube 12 | MP1 | 3.0 | Tube 24 | MP1 | 2.9 | | | |
| | MP2 | 2.0 | | MP2 | 2.5 | | | |

*Materials of bottom panel tubes and membrane strips*

The bottom panel is made of membrane walls which form seamless tubes with dimensions of Ø76.1 × 4.5 mm, and membrane strips of width 23.9 mm, 6 mm thickness and a pitch of 100 mm. Seamless tubes are made of material P235 GH TC1. This material belongs to a group of steels used for working at elevated pressure and temperature, such as in the case of steam generators, boilers and distributors. It can be used at temperatures up to 450 °C.

Depending on the welding position and thickness, filler materials can be applied, whose selection is based on the information provided by the manufacturer, in terms of demand in production and the function of the structure. The steels can be welded within all thickness ranges according to general rules of the welding procedure, by manual or automated welding techniques. Chemical composition of the base material used for the tubes is shown in Table 2, whereas its mechanical properties are given in Table 3. Membrane strips are made of structural steel S235 JRG2, mainly used for shipping containers, steel bridges, vessels and tanks, for preventing atmospheric corrosion. The chemical composition and mechanical properties are given in Tables 4 and 5, respectively.

Table 2. Chemical composition of steel P235 GH TC1, /11/.

| Element | C | Si | Mn | Cr | Mo | P | S |
|---|---|---|---|---|---|---|---|
| max. wt. % | 0.16 | 0.35 | 0.6-1.2 | 0.3 | 0.08 | 0.025 | 0.015 |

Table 3. Mechanical properties of steel P235 GH TC1, /11/.

| $R_e$ (N/mm$^2$) | $R_m$ (N/mm$^2$) | $A_s$ % |
|---|---|---|
| 235 | 360 - 480 | 24 - 25 |

Table 4. Chemical composition of steel S235 JRG2, /12/.

| Element | C | Si | Mn | Cr | Mo | P | S |
|---|---|---|---|---|---|---|---|
| wt. % | max 0.2 | 0.55 | max 1.4 | max 0.3 | max 0.08 | max 0.045 | max 0.045 |

Table 5. Mechanical properties of steel S235 JRG2, /12/.

| $R_e$ (N/mm$^2$) | $R_m$ (N/mm$^2$) | $A_s$ % |
|---|---|---|
| 215 | 340 | 24 |

*Repairing of the boiler bottom panel*

During exploitation, the lower floor screen is subjected to variable thermal loads due to frequent turning on and off the boiler in the heating season. As previously mentioned, thinning of the tube parent material in the zone facing the boiler firebox (upper side of the tube) is detected in the part where the membrane strip is connected to it. After performing damage analysis, repair and welding plans are developed. The repair plan starts with determining the reasons for repair, and for that purpose the following activities are undertaken:

- selection of the welding procedure,
- determining the preheating temperature (if necessary),
- selection of filler material,
- determining the number of passes (layers),
- surface preparation,
- determining the welding parameters,
- determining possible subsequent heat treatment.

Repairs are performed on all 35 tubes in the boiler bottom panel, which extended the scope of repair as mentioned in the previous part of the text. The cutting of the bottom panel is performed at a distance of 3500 mm from the front screen. After cutting and dismantling the tubes, they were replaced with new seamless tubes of Ø76.1 × 4.5 mm, made of steel P235 GH TC1 and membrane strips of width 23.9 mm, 6 mm thickness, of steel S235 JRG2. The material used for seamless tubes is 0.5 mm thicker than the one used for the original bottom panel tubes. During the selection of the welding procedure and performed welding activities, it is decided to use both the MAG and gas-flame welding procedures for repair purposes.

The selection of filler material is made according to the carbon content and other alloying elements in the parent material, as well as the cleaning technique. For achieving bottom panel parent material quality, and the quality of new materials built into it, component geometry after preparation and conditions to which the tubes are subjected, adequate welding consumables are selected, in relation to the chosen procedure. In the case of replacing the existing seamless tubes of the bottom panel with new tubes, the gas-flame welding procedure is selected, with wires VP 42 Ø2.0 and Ø3.0 mm (by Železarna Jesenice) as consumables for the final pass. VP 42 is a copper coated wire suitable for gas-flame welding of non-alloyed steels, tube steels, and boiler sheets. For connecting the new tubes and membrane strips, the arc welding procedure is chosen with active gas shielding (MAG) and consumable VAC 60 Ø1.2 mm wire (also by Železarna Jesenice). VAC 60 is a copper coated wire for welding with a shielding gas, i.e. intended for MIG and MAG welding procedures. It is suitable for welding non-alloyed steels whose tensile strength does not exceed 530 MPa, such as boiler sheets, fine grained- and tube steels.

Commercial designations, electrode manufacturers, chemical composition, and mechanical properties of commercially available pure weld metal are shown in Table 6.

After selecting the filler material, all of the damaged tubes are cut along the cutting line from the bottom panel (35 tubes with a length of 3500 mm), and are adequately prepared. Upon cutting, the ends of seamless tubes are prepared for welding according to the technology prescribed by WPS documentation, wherein the edges of tube ends are filleted, cleaned and degreased. Cleaning is performed using steel brushers and grinding. Figure 6 shows prepared tubes immediately before they are subjected to welding.

Table 6. Chemical composition and mechanical properties of welding consumables, /13/.

| Commercial designation | Manufacturer | Chemical composition, wt. % | | | | | Mechanical properties | | |
|---|---|---|---|---|---|---|---|---|---|
| | | C | Mn | Si | Cr | Ni | $R_e$ (MPa) | $R_m$ (MPa) | Hardness (HB) |
| VP 42 | Jesenice | <0.15 | 1.1 | <0.25 | - | 0.50 | 310 | 410-560 | 110-130 |
| VAC 60 | Jesenice | 0.08 | 1.50 | 0.90 | - | - | 420 | 500-640 | - |

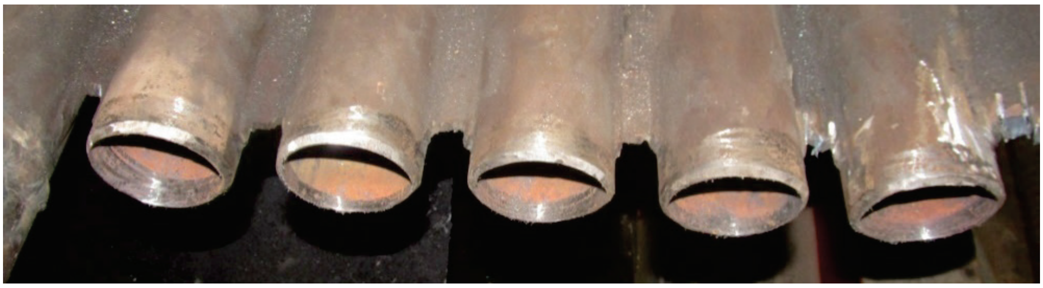

Figure 6. Preparation of bottom panel boiler tubes for welding; edges are filleted, degreased and cleaned.

Welding, i.e. connecting old and new membrane strips and tubes is performed in accordance with defined WPS lists. Prior to developing these lists, the welding technology qualification record is made (WPQR). In the following section is the flow of repair process activities. Ends of new seamless tubes built into the boiler firebox are also prepared in accordance with the technology provided by contractors. Tubes are connected using multi-pass gas-flame procedure without preheating and additional heat treatment. The appearance of welded tubes is shown in Fig. 7.

After welding new and old tubes, the welded joints are tested by radiography. Tests are performed by the Welding Institute in Belgrade. The welding was successful (no defects in welded joints), and the next stage involved welding of membrane strips to tubes without preheating and additional heat treatment. It was performed also in a single pass. Membrane strips are connected to tubes using MAG procedure. Welding parameters for connecting membrane strips and tubes are given in Table 7.

Figure 7. Joining new and old tubes of the bottom panel.

Table 7. Welding parameters for joining membrane strips to tubes.

| | |
|---|---|
| Welding procedure | MAG |
| Consumable material | VAC 60 |
| Radius (mm) | Ø1.2 |
| Current | 135-150 A |
| Voltage | 23 V |
| Current type, polarity | DC+ |
| Gas flow | 17 lit./min |

After the repair, along with all activities and testing, the whole boiler is subjected to strength testing using water pressure. The pressure value 20.8 bar is determined in accordance with the boiler technical documentation and has not been changed during the test. The test medium used for this purpose was water, and involved the use of a control manometer with the measuring range of 0-25 bar, with the accuracy of 0.6. Test duration was 30 minutes. During the test and immediately after, there were no signs of moistening, dewing or leaking in the parent material or welded joints in the panel walls of the boiler. There were no signs of deformation in the components in question. Afterwards, radiographic tests were performed on old and new welded tubes and the connections between them and membrane strips, within the scope of 50% and 100%, respectively. These tests have determined that the defects are within acceptable limits, as defined by the standard SRPS EN ISO 12517. Water pressure and radiographic testing suggested that the boiler (manufactured by Remming) is ready for exploitation.

## DISCUSSION AND CONCLUSION

The remaining sulphuric acid inside the boiler does not cause corrosion of heating surfaces, however if the tubes are slightly slanted inside the installations, the acid may accumulate. Sulphuric acid aggressively acts on the metal, leading to damages in the material, as is shown here. In most cases, sulphuric acid causes the thinning of tube walls which can lead to catastrophic failure, possibly with fatal consequences. Low-temperature corrosion is the most common type of damage encountered in heating plant components.

For the purpose of detecting the level of damages, an independent third party is employed to perform non-destructive inspection. After determining and defining the level of damage, repairs went underway. For performing repairs as successfully as possible, an appointed body was also involved to monitor the repairs.

In order to ensure that the repairs are as successful as possible, it was necessary to perform the inspection on several shutdown occasions:

- defining damage levels and cutting lines,
- reviewing and approval technical documentation regarding the repair by the appointed body,
- inspection during the dismantling of damaged tubes and the preparation of new tubes to be welded to the old ones,
- performing radiographic tests after welding old and new tubes, and
- final strength tests by cold water pressure that followed the completion of the repairs.

High quality repairs can be expected when all welding technology (WPS lists) requirements have been met. In addition, the significance of WPQR can be obviously seen in the verification and defining of the final WPS list according to which all welding activities are undertaken. It is necessary to conduct intermediate inspection at shutdowns, and follow it by non-destructive testing methods in order to avoid defects in the welded joints, which could lead to equipment downtimes during later exploitation. In addition to all of this, it is also necessary to employ an appointed body for pressure equipment for monitoring these types of repairs and obtaining approval for necessary welding technologies.

Based on the metallographic analysis, it is concluded that the detected microstructural state of the surface at the tested location of the tube complied with the state expected of the declared material. In addition, it is concluded that the tested tube complies with safety requirements for the prescribed boiler operating parameters, from the standpoint of the detected surface state. This, of course, holds in the case it is confirmed by other NDT methods.

In the example presented here, the repair procedure, i.e. the replacement of the bottom panel is determined as an adequate solution, taking into account that the repair was performed in August 2016, and that during the heating season of 2016/2017, there were no downtimes or any other exploitation related problems with the equipment. Successful repairs were preceded by an unsuccessful one, as can be seen, which resulted in the need to extend the scope of the repair process. These changes to the repair process resulted in increased economic costs, including the costs of the repairs themselves, the costs of repeated measurements and also the indirect costs due to downtime and extended repair time.

Repair welding eliminated the issue of damaged tubes, but not the cause of the problem itself, thus it would be advised to consider the introduction of more frequent NDT control of all critical locations in the boiler in question, taking into account that this was the third intervention on the boiler since it was put in exploitation. One solution definitely involves the reconstruction of this equipment in a way that would fix the poor technical solutions which had led to the low-temperature corrosion damage in the first place.

ACKNOWLEDGEMENT

The authors of this paper acknowledge the support from the Serbian Ministry of Education, Science and Technological Development for projects TR35040 and TR35011.

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