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ROOT-CAUSE ANALYSIS OF SUPERHEATER-TUBE FAILURE

ANALIZA GLAVNEGA VZROKA NAPAKE CEVI PRI PREGREVALNIKU

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Superheater-tube failure is listed among the major causes of a fossil-fuel-fired boiler outage. Therefore, it is necessary not only to identify and repair it in the case of failure but also to eliminate the root cause of this problem. As there may be multiple reasons of failure in exposed equipment such as a superheater, a thorough investigation of more than one probable cause is usually required. This article focuses on a failure analysis of a boiler located in a chemical plant. After a leak was discovered, several cracks on the superheater tubes were identified as its main cause. It was necessary to assess the extent of the damage, detect the root cause and propose corrective actions. Two problematic locations with cracks were identified during the visual inspection: the first was on the superheater-tube bends and the other was the weld joint between the superheater and the transition pipe. As the first step, the material-microstructure and composition analyses of the tubes in these critical locations were carried out. Even though small weaknesses were found in the microstructure, the main cause of the tube failure was not identified. As the next probable cause, thermal-dilatation stresses were investigated using the finite-element analysis (angl. FEA). The support system, consisting of fixed and spring supports, as well as the compensator were included in the analysis that confirmed the thermal-dilatation stresses as the major cause of the failure. Based on the results, a new technical solution for the supports was suggested and verified with the FEA.

Keywords: corrosion, weldment cracks, superheater supports, thermal dilatation

Napaka cevi pregrevalnika je znana kot ena najpogostejših napak pri kotlu na fosilna goriva. Zato jo je treba, ne le prepoznati in v primeru okvare popraviti, pač pa tudi v splošnem odpraviti vzrok za njen nastanek. V tako izpostavljenem elementu kot je pregrevalnik, je za tovrstno napako lahko več vzrokov, zato je za ugotovitev le-teh, potrebna temeljita preiskava. Članek je osredotočen na analize okvar kotla, ki se nahaja v kemični tovarni. Potem, ko so odkrili puščanje, je bilo na pregrevalnih ceveh več razpok, ki so bile opredeljene kot glavni vzrok. Treba je bilo oceniti obseg škode, odkriti vzrok in predlagati ukrepe za popravilo. Med vizualnim pregledom sta bili ugotovljeni dve problematični lokaciji z razpokami. Prva na zavojih cevi pregrevalnika in druga v spoju zvara med pregrevalnikom in prehodno cevjo. Najprej je bila izvedena analiza mikrostrukture materiala in analiza sestave cevi na kritičnih mestih. Čeprav so bile ugotovljene pomanjkljivosti v mikrostrukturi, glavni vzrok napake cevi ni bil ugotovljen. Naslednji možni vzrok bi lahko bila termodilatacijska napetost, ki je bila raziskovana z uporabo analize končnih elementov (FEA). Sistem za podporo, ki je sestavljen iz fiksnih in podpornih vzmeti pa tudi kompenzator, so bili vključeni v analizo, ki je potrdila, da je toplotna dilatacijska napetost glavni vzrok napake. Na podlagi rezultatov je bila predlagana nova tehnična rešitev "podpor", ki jo je potrdila tudi FEA.

Ključne besede: korozija, razpoke pri zvarih, pregrevalnik, termodilatacija

1 INTRODUCTION

Boilers are common parts of many process units. Since their life expectancy can be counted by decades (usually 200,000 working hours), some minor or bigger problems are inevitable. Regular inspections are carried out after some time to find problematic areas and establish corrective actions to prevent failure. The boiler life expectancy may vary based on the material used, working conditions, boiler operation history, etc. One of the most exposed boiler parts is the superheater, which is one of the crucial heat-exchanger types among the heat-exchanger applications. Its main advantage is the reduction of fuel consumption, but it is also susceptible to various types of damage such as creep, deflection, damage caused by environmental influences and mechanical loads.

According to D. R. H. Jones[1], the superheater is the most commonly damaged part of a boiler, thus regular inspections are necessary to check its condition. The main damage reasons can be divided into three major categories:

- Mechanical – caused by a higher stress and strain at a specific location (deflection, cracks, weldment damage);
- Corrosion – material-structure deformation due to various corrosion mechanisms;
- Erosion – damage caused by the particles in the medium flow.

H. Othman[2] faced a similar problem of superheater-tube deformation and cracks near the weldments. He found that the main factor causing the problems was the temperature of 520 °C, which caused temperature dilatations. As soon as the supports did not allow compensation of dilatation stresses, deformation and cracks of the pipes occurred.

2 BOILER DESCRIPTION

The analyzed boiler located in the chemical power plant has been in operation for a long time under various conditions, which differed from the original design conditions. Therefore, regular inspections of critical areas were necessary. Boiler design parameters are: a steam production of 50 t/h, the nominal pressure of superheated steam of 3.8 MPa and the nominal temperature of superheated steam of 375^{+15}_{-10} °C. The boiler consists of several crucial parts. The article is focused only on superheaters (referred to as P1 and P2) and the U-shaped transition pipe between them. During one of the inspections, cracks and perforations were revealed in the area of weldments near the inlet chamber of superheater P2 as well as cracks and leakage on the superheater-P2 pipe bend.

2.1 Description of superheaters

The construction of these superheaters is classic, widely used all over the world. Both of them are similar, having the same dimensions and being situated one above the other. The output chamber of superheater P1 is connected with the input chamber of superheater P2 by the U-shaped transition pipe. Each superheater has 9 pipes in 4 rows (a total of 36 pipes), which go through the membrane wall, with which they are connected by a seal-weld joint (**Figure 1**).

The presented article is focused on superheater P2, which was exposed to a medium with a temperature of 335 °C and a pressure of 4.0 MPa (**Figure 2**). Another crucial part is in the U-shaped transition pipe where cooling water is sprayed to achieve the required steam properties.

2.2 Description of the supports

Superheater collectors are supported by two fixed strap iron profiles (**Figure 2**).

The U-shaped transition pipe has spring supports on three locations (**Figure 3**). Two of them are at the upper part with displacements of 15 mm and 23 mm and one at the bottom part with a displacement of 75 mm.

Figure 1: Part of superheater P1 and the membrane wall
Slika 1: Del super grelca-pregrevalnika P1 in stena membrane

Figure 2: Support of the superheater collector
Slika 2: Del zbiralnika v pregrevalniku

2.3 Damaged areas

As mentioned, there are two main problematic areas. One of them includes the crack and the leakage on the superheater-P2 pipe bend (**Figure 4**).

Another problem was the crack near the weld on the superheater collector with the U-shaped transition pipe (**Figure 5**). This problematic part had been repaired several times in the past, which can be seen in the figure.

The structure of the material was expected to be one of the possible root causes of the damage, mainly the dislocations in the structure. Critical imperfections may have been developed not only during the equipment operation but even during its manufacture. In the following step, two samples from the damaged areas were taken for a metallurgical analysis to prove the dislocation presence. The conformity with the declared chemical composition and mechanical properties of material 1.0405 were tested. A spectrometric analysis was per-

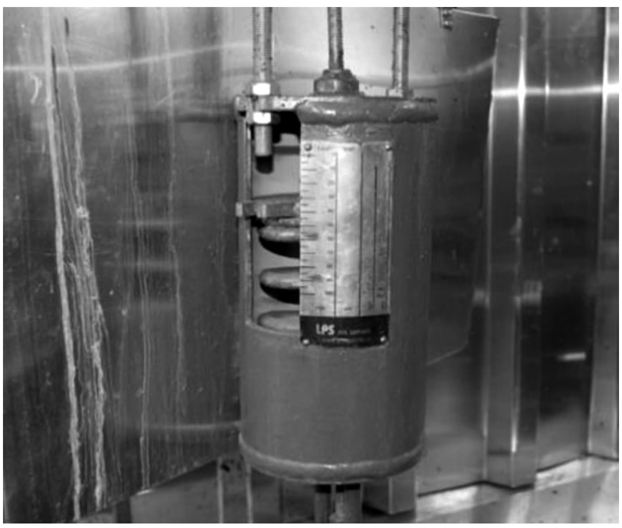

Figure 3: Spring support of the transition pipe
Slika 3: Vzmet v pretočni cevi

Figure 4: Leakage on superheater-P2 pipe bend
Slika 4: Puščanje na P2 pregrevalniku na krivini cevi

Figure 5: Crack near weld on the superheater-P2 collector metallurgical analysis
Slika 5: Razpoka blizu zvara na pregrevalniku P2 metalurška analiza zbiralnika

formed (Method – 12-MTL-5.4/07 program Fe-10) as well as a tensile test (Method – ČSN EN ISO 6892-1B). The tests proved that all the values were within the limits.[3]

The first sample was taken from the pipe-bend area because the visual inspection revealed a horizontal crack (length 25 mm) on the pipe bend. This kind of crack cannot have been caused by the bending process. However, the manufacturing process should have influenced the material structure by lowering its corrosion resistance. The purity results of the analyses proved the material to be of a very good quality.

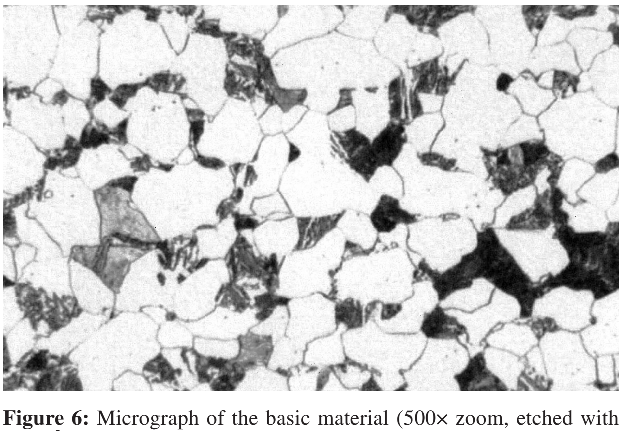

Figure 6: Micrograph of the basic material (500× zoom, etched with Nital)[3]
Slika 6: Posnetek osnovnega materiala (500× povečava, jedkano z Nitalom)[3]

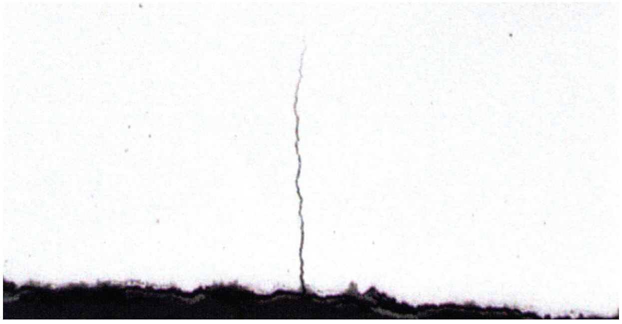

Figure 7: Crack located on the inner surface of the pipe (50× zoom)[3]
Slika 7: Razpoka, locirana na notranjostipovršine cevi (50× povečava)[3]

Afterwards, the corrosion that was found on both surfaces of the pipe was examined. Pitting and small sharp projections were found on the inside. Some of the pits already had a character of small cracks (**Figure 7**), caused by a combination of corrosion and stress. Based on these findings, it was expected that the cracks had started on the outside of the pipe, in the area where the material was weakened by the small cracks from the inner side. Stress and the medium flow might be important during the process of crack growth and will be further examined.

The second tested sample was taken from the area where the collector is welded to the U-shaped transition pipe. The crack goes through the whole weld and is divided into two branches in the middle of the cross-section (**Figure 8**). The crack is open mainly in the middle part and even with the microscope analyses, the direction of the crack formation could not be determined.

There were no defects found either in the material structure or in terms of material properties that would directly influence the crack formation. Only some small

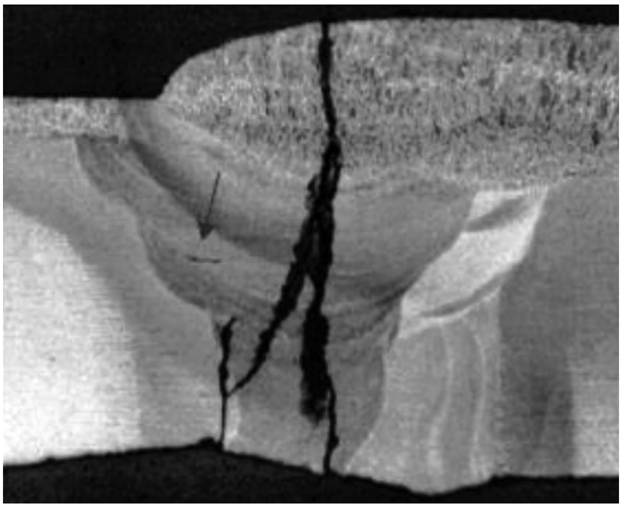

Figure 8: Weld macrosection with the crack (5× zoom)[3]
Slika 8: Prerez zvara z razpoko (5× povečava)[3]

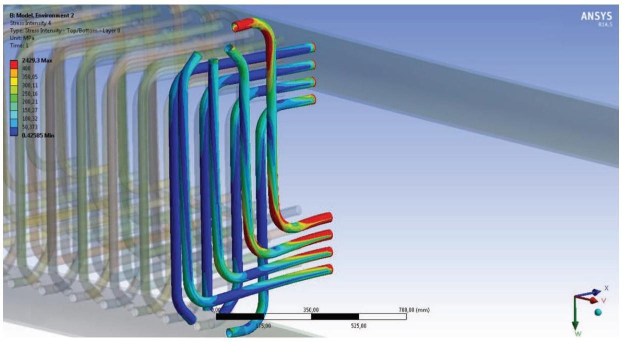

Figure 9: Stress intensity for bent pipes
Slika 9: Intenzivnost napetosti na zvite/zavoje cevi

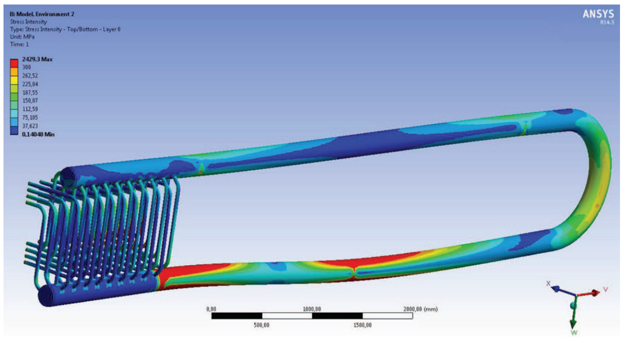

Figure 10: Stress intensity for the whole computational model
Slika 10: Intenzivnost napetosti za celoten model

defects were found (see the black arrow in **Figure 8**). As mentioned above, this weld was repaired several times in the past so it was obvious that there was some problem with the equipment geometry (e.g., supports locations), stress and temperature dilatation.

To fully understand the root cause of the crack formation, stress analyses were carried out.

2.4 FEM analyses

As the material analysis did not show the root cause of the problem, finite-element analyses were used. A shell model of the two collectors (one from each superheater) connected by the U-shaped transition pipe was prepared in SolidWorks. For the analyses, we used computational program ANSYS® Academic Research, Release 14.5.

2.5 Mathematical model preparation

Steady-state thermal analyses and their combination with static structural analyses were performed. At first, the model geometry was imported from SolidWorks to ANSYS Workbench and material properties were set up for material 1.0405. In the next step, a computation mesh, which had approximately 150,000 elements, was created.

2.6 Simulation of current conditions

After preparing a sufficient mesh, appropriate boundary conditions (BCs) were set up. These included the standard earth gravity (g = 9,8066 m/s^2), fixed supports (at the place where the collector pipes were connected to the membrane wall and also at the places of collector supports), the internal pressure, the temperature and displacements (at the place where three spring supports were located). The last three BCs varied based on the analysis type. Two load cases were considered:

Design conditions:

First, an analysis based on design parameters was performed. The internal pressure (4.01 MPa) was applied to all the surfaces as well as the temperature (334 °C). Spring supports were replaced with a direction displacement, which prevented the movement in the vertical direction. Although the stress value was slightly higher in the area of pipe bends, it was not high enough to initiate a crack formation.

Operational conditions:

To examine the problematic areas, it was necessary to apply operational conditions. Therefore, to all the surfaces, the internal pressure (p = 3,61 MPa) and two different temperatures were applied because, as mentioned above, there is a part of the U-shaped transition pipe where the cooling water is sprayed. This was the part where the temperature varied. The first temperature (T_{max} = 332 °C) was used for one collector with pipes and the second temperature (T_{min} = 278 °C) was used for the second collector and the part of the U-shaped transition pipe. At first, all the other BCs remained unchanged but the stresses still were not high enough. This is why one of the BCs was changed and the spring supports were simulated with the exact values of the direction displacement (as mentioned before, these included 15 mm, 23 mm and 75 mm). The results of this analysis were identical to our problem and they confirmed our expectations that the problematic parts of this construction are the spring supports.

As can be seen on **Figure 9**, the stress intensity is crucial in the pipe bends, the exact location where the crack and leakage were discovered.

An improper use of the supports was confirmed by a higher stress intensity at the second problematic location including the collector and the U-shaped transition-pipe weld joint (**Figure 10**).

Based on these results, it was obvious that the problematic parts were the supports. They allow higher values of the total displacement of the U-shaped transition pipe that induce higher moments and stresses. Also, there is one support at the bottom part, witch behaves like the center of rotation; thus, an additional stress is induced. The other crucial elements were the fixed supports of the collectors, located too close to the weld-joint location.

2.7 Support modification

In order to avoid financial losses caused by repeated shutdowns and repairs, multiple corrective measures were proposed. The modification of the supports, which led to a stress reduction at the crucial areas, was performed. It was achieved by increasing the spring stiffness, which influenced the BC displacement. Due to this modification, each displacement was reduced by almost a half of the previous value (10 mm, 20 mm and 35 mm). Unfortunately, the results proved that the stress intensity decreases insufficiently and the spring modification is not sufficient to fix the problem. Another improvement could take the form of minimizing the displacements or removing the bottom support, identified as problematic. This would lead to a further decrease in the stress levels in the critical areas. However, these analyses are not included in the article.

3 CONCLUSIONS

The paper focused on superheater damage. Cracks and leakage were found in several crucial areas; thus, material and FEM analyses were carried out. The analyses proved that the main cause of the problems was an inappropriate support of the U-shaped transition pipe. The problem was caused by a vertical displacement and also by the spring-support location, combined with the fixed supports of the collectors near the weld location. Due to the surface stresses induced in the problematic areas, this place is the most ideal for a crack formation based on shape discontinuities, heat treatment and material discontinuities. Based on the analysis results, a reduction of the support displacements and a change in their location form the easiest and fastest way to prevent increased values of the stresses and further crack formation and propagation.

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