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# INTEGRITY AND RISK ASSESSMENT OF RECONSTRUCTED STEAM LINE

# PROCENA INTEGRITETA I RIZIKA REKONSTRUISANOG PAROVODA

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**Keywords**
- steam line
- pressure vessel
- stress analysis
- microstructure
- structural integrity

*Abstract*

*The integrity assessment of high pressure steam pipeline primarily requires stress state determination, including not only effects of working pressure and temperature, but also all acting loads. Toward this aim, the application of numerical methods for calculating the stress state is the best option. Here, the integrity assessment of one of the collectors of the RA line at Block 1 of 'Nikola Tesla' B Thermal Power Plant is shown, which was the subject of reconstruction due to a manufacturing defect in one of the welded joints. Integrity and risk of the steam line is assessed using fracture mechanics parameters, including microstructural analysis.*

**Ključne reči**
- parovod
- posuda pod pritiskom
- analiza napona
- mikrostruktura
- integritet konstrukcije

*Izvod*

*Procena integriteta parovoda pod visokim pritiskom zahteva prvenstveno utvrđivanje naponskog stanja materijala, pri čemu treba uzeti u obzir ne samo uticaj radnog pritiska i temperature, već i sva delujuća opterećenja. Primena neke od numeričkih metoda proračuna za analizu naponskog stanja je najbolji alat. Ovde je prikazana je procena integriteta jednog od kolektora RA linije na Bloku 1 Termoelektrane 'Nikola Tesla' B koji je bio predmet rekonstrukcije zbog greške na jednom od zavarenih spojeva. Integritet i rizik parovoda je procenjen primenom parametra mehanike loma, uz analizu mikrostrukture.*

## INTRODUCTION

High pressure steam lines are critical components in thermal power plants, so they require considerable attention during exploitation in order to maintain necessary levels of reliability, /1/. In the scope of steam line analysis (design, exploitation, remaining life assessment), one should take into account working parameters, pressure, temperature, and other factors such as the quality level of welded joints, since they represent the most critical parts of a steam line. Integrity assessment is typically performed after a certain exploitation period and is required due to eventual damage of steam line by internal loads (pressure, temperature), and external ones (forces, moments), /2-6/. Hence, application of numerical methods, such as finite element method (FEM) for stress state calculation is the best option, /7/. In addition, microstructural and non-destructive tests are necessary to confirm if welded joints meet quality requirements, /8/.

## FACILITY DESCRIPTION

The existing steam line is a part of the RA line located at block B1 and is made of steel X20CrMoV12-1 (DIN) during powerplant construction in the eighties. A reconstruction of its main and auxiliary fresh steam RA lines was initiated after a couple of cracks were detected in welded joint regions, along with microstructural test results of the material, based on which it was concluded that significant aging occurred in the material during exploitation. As such, the steam line was assessed as unsafe and unreliable for further use, which necessitated reconstruction work. In this way, regular exploitation of the pipeline in working mode could carry on, whereas preheater connections and high pressure turbines would be subjected to lower loads than the existing ones. Reconstruction involved complete replacement of the main fresh steam RA line, including its secondary drainage and heating lines, with a newly selected material, steel X10Cr MoVNb9-1, as well as support systems and other elements and equipment for the block B1 of TENT-B.

## DAMAGES ON STEAM LINE

Extensive assembly work during reconstruction of the RA line was preceded by an ever more extensive process of prefabricating steam line parts in workshop conditions. During the final non-destructive tests of the fresh steam RA line, it was determined that one of the welded joints does not fully meet the quality requirements. Volumetric and surface indications detected in the material were still within acceptable limits, but it was also determined that hardness values in the welded joint and parent material of 1RA30-B24 collector, in the vicinity of pipes and lids, were below acceptable level. Figure 1 shows the location of the region where measured hardness values were below minimal values according to the relevant standard.

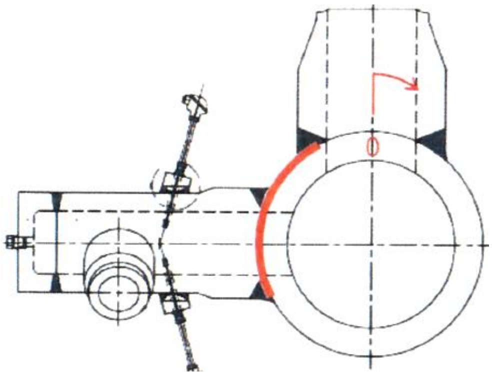


Figure 1. 1RA30-B24 collector, with a detailed view of the region with measured hardness levels below the allowed minimum.

The region marked in red in Fig. 1 depicts hardness values in the parent material from 120 to 160 HB, whereas values in the weld metal were slightly higher, 150-170 HB.

In order to meet the quality requirements for steam line welded joints, it was necessary to reconstruct the collector. Thus, there was a need to remove the region with the detected insufficiently hard material. Next, a new lid was to be manufactured and installed.

The X10CrMoVNb9-1 parent material for a fresh steam line underwent considerable microstructural changes during both the welding process and post-welding heat treatment.

a)

b)

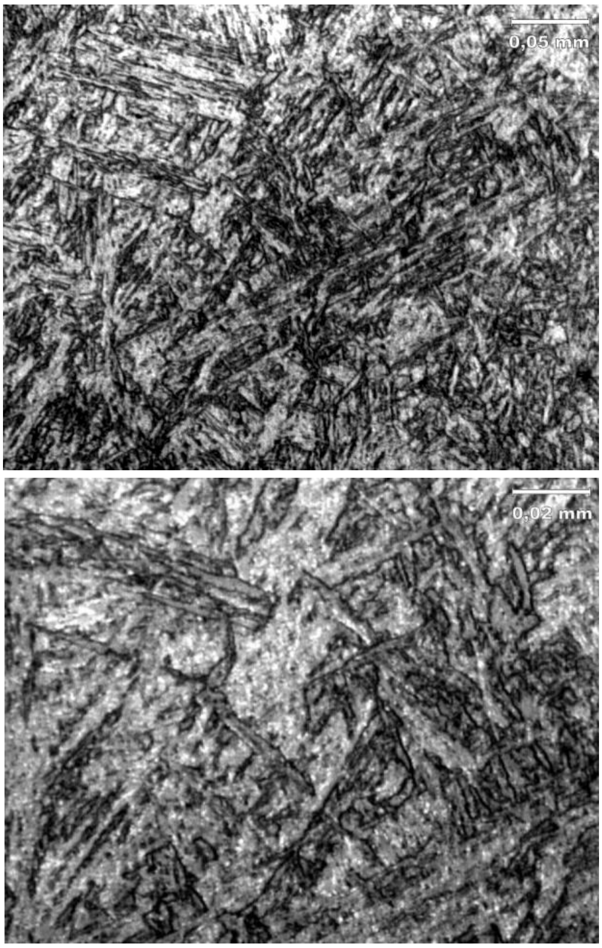



Figure 2. Microstructure of X10CrMoVNb9-1 (219 HB), magn. 200× (a), and 500× (b), showing the region with satisfactory microstructure.

The steel X10CrMoVNb9-1 microstructure is shown in Fig. 2, as the result of replica method used on a part of the parent material that was not damaged, with 200× and 500× magnification. It can be concluded from this replica analysis that tempered martensite is present in the microstructure which corresponds to the expected state of the material. Such structure is also present in the areas with no detected damage.

In addition, the region with lower than expected hardness values for steel X10CrMoVNb9-1 were obtained using the replica method (Fig. 3), with 200× and 500× magnification. After performing replica analysis it was determined that the weld metal microstructure underwent significant transformation. Due to this, ferrite was dominant in the microstructure in the form of a carbide mix, whereas tempered martensite, typically encountered in this material, appeared only in traces. All this points towards preheating of the material during the heat treatment.

a)

b)

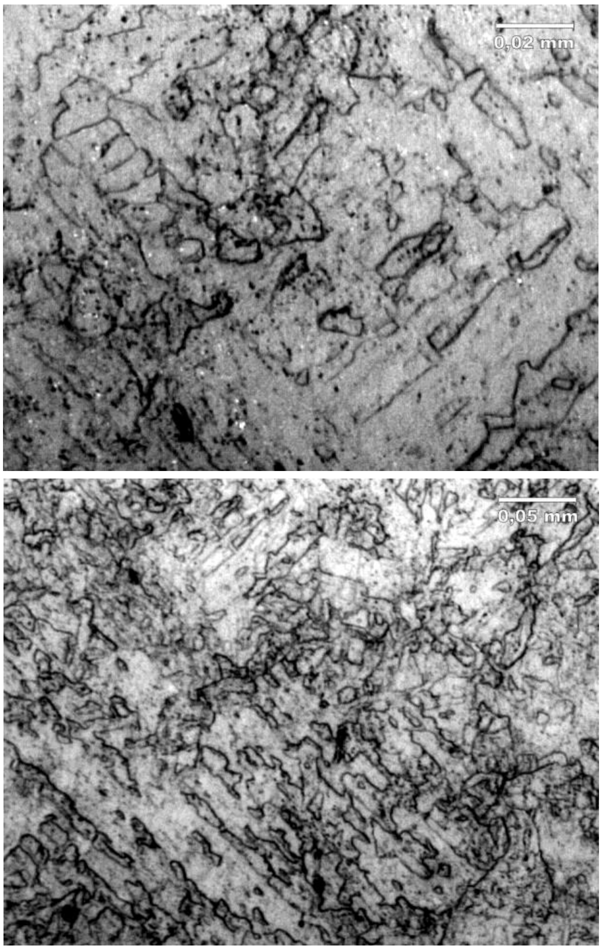



Figure 3. Microstructure of X10CrMoVNb9-1 (143 HB) at the collector pipe, magn. 200× (a), and 500× (b), material with unsatisfactory microstructure.

Collector lid material in the immediate vicinity of the welded joint underwent microstructural changes, along with pipe material, Fig. 4. Ferritic microstructure was dominant again in the form of carbide mix, whereas tempered martensite was almost entirely absent.

Considering that the replica method confirmed hardness results that were below the minimal level in certain regions, it was determined that material degradation was indeed caused by preheating during post-weld heat treatment.

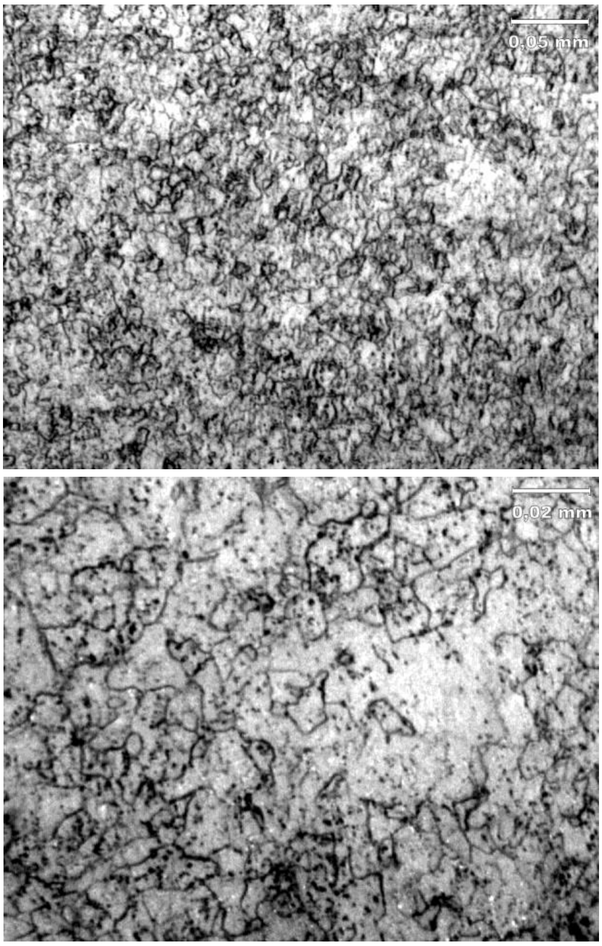
a)
b)



Figure 4. Microstructure of X10CrMoVNb9-1 (142 HB) of the collector lid, magn. 200× (a), and 500× (b), material with unsatisfactory microstructure.

Now, the stage is set for steam line reconstruction, including repair welding, as the most important process, /9, 10/.

STEAM LINE RECONSTRUCTION

Chemical composition and mechanical properties of steel X10CrMoVNb9-1 are given in Tables 1 and 2, respectively. In addition, Table 2 provides mechanical properties of this material at room- and RA line operating temperatures.

Table 1. Chemical composition of steel X10CrMoVNb9-1 (wt.%).

| El. | C | Mn | Si | S | P | Cr | Mo | Ni | V | Nb |
|---|---|---|---|---|---|---|---|---|---|---|
| % | 0.08-0.12 | 0.3-0.6 | 0.2-0.5 | 0.01 | 0.02 | 8-9.5 | 0.85-1.05 | 0.4 | 0.18-0.25 | 0.06-0.1 |

Table 2. Mechanical properties of steel X10CrMoVNb9-1.

| Test temp. [°C] | $R_{p0.2}$ [MPa] | $R_m$ [MPa] | A [%] | Z [%] | HT [HB] | KV [J] |
|---|---|---|---|---|---|---|
| room | ≥450 | 620-850 | ≥20 | ≥40 | 200-248 | ≥68 |

WELDING PROCEDURE

Steam lines have very strict demands in terms of welded joint quality due to hazards related to the working fluid. Hence, particular attention needs to be devoted to proper selection of the welding process. Figure 5 shows the groove geometry at pipe and collector lid connection, using X10Cr MoVNb9-1 as parent material along with groove fill plan.

The required welded joint quality level can be achieved via appropriate preheating at temperatures ≥ 220 °C, wherein welded joints are subjected to stress annealing at 740 °C after welding, with a total duration of 180 min. This heat treatment process is performed in order to remove residual stresses that occurred during martensitic transformation, thus producing a tempered martensite structure.

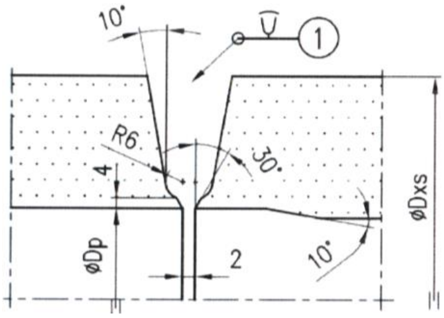



Figure 5. Groove geometry and fill plan for a circular welded joint between collector lid and pipe; material - X10CrMoVNb9-1.

Welded joints were made using a combination of TIG and MAW processes. The root pass was done using TIG, with C9 MV-IG filler material manufactured by Böhler, /11/, with 100 % Ar as shielding gas. Fill passes were done using MAW, with a coated electrode FOX C9 MV, also manufactured by Böhler, /11/. This electrode was previously dried at 300 °C for 2.5 h.

POST-WELD TESTING

In order to verify the reconstruction technology for the collector lid, welding activities were followed by NDT, and considering that it was not possible to perform cold water pressure tests, a numerical model which would simulate loads in working conditions was developed. The following NDT methods were used: visual, magnetic particle, ultrasonic, replicas, and hardness measurement.

NON-DESTRUCTIVE TESTING

Since high-risk pressure equipment is involved it was necessary to perform a detailed NDT to prove that welded joints met the requirements of quality class B, according to standard SRPS EN ISO 5817, /12/. Unacceptable defects were not found.

FINITE ELEMENT METHOD

Numerical simulation of the stress state was made to provide additional confirmation of collector integrity, using static pressure of $p$ = 20.6 MPa. The stress state and the finite element mesh for the RA collector model are shown in Fig. 6, indicating maximum value $\sigma_{max}$ = 213.6 MPa.

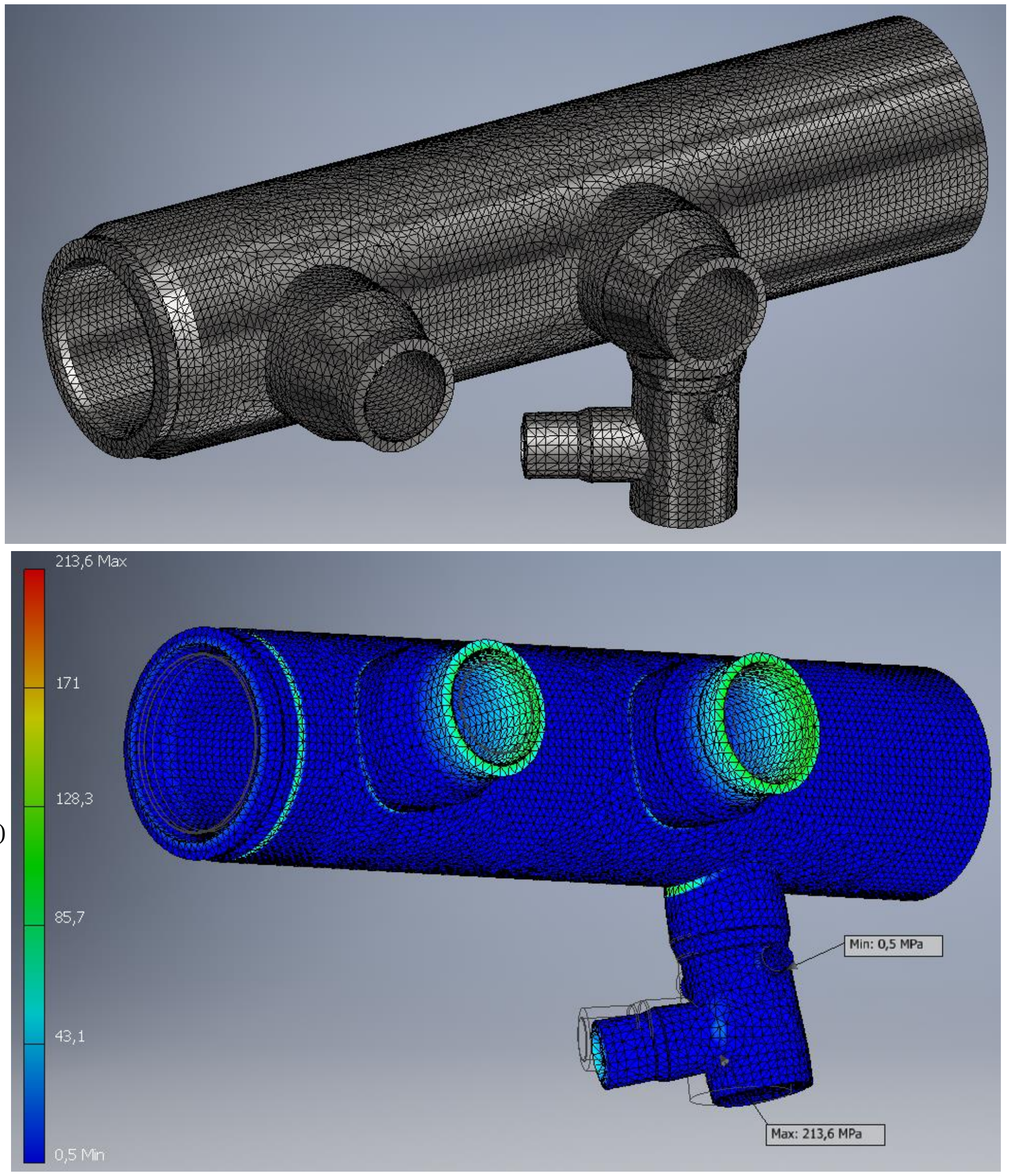



Figure 6. Finite element modelling: a) finite element mesh; b) stress state in the collector.

INTEGRITY AND RISK ASSESSMENT

To assess structural integrity of the steam line, the FAD is used. Fracture toughness $K_{Ic}$ for the weld metal is taken as 1580 MPa$\sqrt{\text{mm}}$, /13/. For case of crack length 1 mm, the stress intensity factor can be calculated by:

$$K_I = Y(a/W)\sigma_{max}\sqrt{\pi a} \qquad (1)$$

where: $Y(a/W)$ is defined by /13/, $Y(a/W) = 1.12-0.26(a/W) + 10.52(a/W)^2 - 21.66(a/W)^3 + 30.31(a/W)^4$, resulting in $Y(a/W) = 1.12$ for $a/W = 0.05$ ($W = 20$ mm). Now, one can get $K_I = 424$ MPa$\sqrt{\text{mm}}$ and $K_I/K_{Ic} = 0.27$.

The ratio between critical cross-section stress and critical stress (half-sum of yield stress, 450 MPa, and tensile strength, 650 MPa) is calculated using the equation:

$$S_R=\sigma_n/\sigma_F=213.6/0.95/550=0.41$$

The coordinates of the point in the FAD (0.41; 0.27) are in the safe area, Fig. 5, at the level of fracture probability, approximately 0.42.

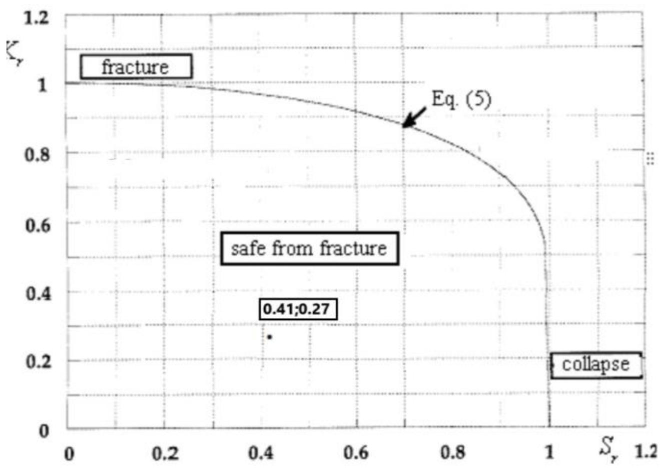



Figure 5. Failure analysis diagram for 1 mm long crack.

Risk level is determined according to the consequence, which is evaluated as highest due to possible damage and fatalities, and probability (medium). Risk matrix can now be obtained in a simple way, as shown in Table 3, indicating high level of risk.

Table 1. Risk matrix for 1 mm long crack.

| | | Consequence category | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 very low | 2 low | 3 medium | 4 high | 5 very high | **Risk level** |
| Probability category | ≤0.2 very low | | | | | | **Very low** |
| | 0.2-0.4 low | | | | | | **Low** |
| | 0.4-0.6 medium | | | | | **Crack 1 mm** | **Medium** |
| | 0.6-0.8 high | | | | | | **High** |
| | 0.8-1.0 very high | | | | | | **Very high** |

## CONCLUSIONS

Technical justifiability of RA line collector reconstruction is reflected in the fact that complete replacement was not possible, whereas reconstruction was necessary in order to ensure safe operation of equipment in question. Additionally, this reconstruction extended the work life of the RA collector, and NDT methods, combined with FEM. The integrity of the reconstructed RA line collector was confirmed in several different ways, but with high risk of failure if a crack would appear.

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