Failure Analysis of SA-213TP347H High-temperature Reheater of 600 MW Supercritical Boiler

Jia’an Wang, Jun He
China Huadian Electric Power Research Institute Co., Ltd., Hangzhou, China
*Corresponding author’s e-mail: jiaan-wang@chder.com

Abstract. Failure analysis of SA-213TP347H steel tube for high-temperature reheater of 600MW supercritical boiler was studied by means of macroscopic analysis, chemical composition, mechanical properties, microstructure, scanning electron microscopy and energy spectrum analysis. The results show that the chemical composition, hardness and strength of the tube samples meet the limit of ASTM A213/A213M standard. The microstructure of tube-burst sample is austenite, there are some precipitates containing Cr and Nb element at the grain boundaries. The test results for the spare part sample near elbow show that the hardness exceeds the limit of SA-213TP347H steel, there are a lot of slip lines and some non-metallic inclusions containing S in the microstructure. It is concluded that solid solution treatment missing in its manufacturing is the main reasons for the fracture, which makes Cr precipitate on the grain boundary and form the Cr-depleted zone, which is easy to cause intergranular stress corrosion and lead to the tube burst.

1. Introduction
SA-213TP347H austenitic stainless steel not only has good intergranular corrosion resistance, high-temperature oxidation resistance, creep performance, but also has good welding and thermal processing performance, which has been widely used in the high-temperature heating surface tubes of ultra-supercritical or supercritical large-capacity boiler [1]. However, in the production of SA-213TP347H steel, some domestic manufacturers did not carry out solid solution heat treatment after cold processing in strict accordance with the standard requirements, or even did not carry out solid solution treatment at all, which caused a great impact on the service performance of TP347H steel, especially the performance of elbow.

On June 22, 2018, the high-temperature reheater of a power plant leaked. On July 12, the leakage of the high-temperature reheater tube happened again. After the leakage, the relevant personnel of the Electric Power Academy rushed to the scene for the first time, and preliminarily judged that the first explosion port was the sixth of the 40nd screen tube from the left of the furnace, and the burst tube was the inside of the U-shaped elbow of the high-temperature reheater. The burst tube material was SA-213TP347H, and the specification was Φ 51 mm x 4.5 mm. The burst tube sample (No. 1) and the spare part (No. 2) were cut off on site, and the tube was analyzed by optical microscope (OM), scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS), etc., so as to find out the reason why the high-temperature reheater frequently leaked.
2. Experiment

2.1 Macroscopic morphology analysis
The explosion position of the high-temperature reheater is located on the arc side of the elbow, and the explosion is extended along the axial direction of the tube. It’s found that the high-temperature reheater elbow is not well formed, and the elbow is triangular in section, forming an indentation during the pressing process. There are excessive defects in the elbow. The surface of the spare part is bright, and it has not been subjected to solution treatment after cold working, and it is magnetically measured by a magnetic measuring instrument. At the same time, the ellipticity of the elbow is measured, and the maximum ellipticity is 17%, which seriously exceed the standard requirements.

2.2 Chemical composition analysis
Table 1 show the chemical composition of sample No.1 and No.2 tubes. The results show that the main composition of the material conforms to the chemical composition requirements of SA-213TP347H steel in ASTM A213/A213M.

Table 1. Chemical analysis results of samples (mass fraction, %)

| Chemical composition | C   | Mn  | S   | Si  | Cr  | Ni  | Nb  |
|----------------------|-----|-----|-----|-----|-----|-----|-----|
| No.1                 | 0.07| 1.5 | 0.004| 0.5 | 17.81| 10.88| 0.778 |
| No.2                 | 0.08| 1.5 | 0.002| 0.5 | 17.81| 10.25| 0.919 |
| Standard value       | 0.04-0.10| ≤2.00| ≤0.030| ≤1.00| 17.0-19.0| 9.0-13.0| 0.8-1.10 |

2.3 Mechanical performance analysis
Table 2 shows the hardness test results of the explosion position (No. 1-1), the distance from the explosion position 400 mm (No. 1-2), and the spare part straight section (No. 2-1), the inner arc surface on the elbow of the spare part (No. 2-2) and the outer arc surface (No. 2-3), each position is measured 3 times. The results show the hardness is consistent with the requirements of ASTM A213/A213M. The hardness of the explosion position is low, and the hardness of the spare part is obviously increased. It may be due to incomplete or no solution treatment of the spare part, and other microstructures existed in the microscopic phase.

Table 3 shows the mechanical tensile test on the fire side (No. L1) and the backfire side (No. L2) of the burst tube, and the spare part (No. L3 and No. L4). The tensile properties meet the requirements of the standard specification.

Table 2. The hardness results of samples (HRB)

| Sample No. | 1     | 2     | 3     | Average value | Standard value |
|------------|-------|-------|-------|---------------|----------------|
| No.1-1     | 58.3  | 63.0  | 62.6  | 61.3          |                |
| No.1-2     | 69.0  | 72.5  | 73.0  | 71.5          | ≤90            |
| No.2-1     | 83.2  | 80.0  | 81.4  | 81.5          |                |
| No.2-2     | 85.7  | 85.0  | 86.0  | 90.6          |                |
| No.2-3     | 83.3  | 83.8  | 82.0  | 83.0          |                |

Table 3. The tensile test results of samples (MPa)

| Sample No. | Sampling locations | $R_{p0.2}$/MPa | $R_m$/MPa | $A$ / % |
|------------|--------------------|----------------|-----------|---------|
| No.1       | L1                 | 284            | 605       | 47      |
|            | L2                 | 279            | 600       | 53      |
|            | L3                 | 284            | 655       | 50      |
| No.2       | L4                 | 274            | 655       | 48      |
2.4 Microstructure analysis

Figure 1 shows the microstructure of the sample on the burst tube, and Figure 2 shows the microstructure of the sample at the elbow of the spare part. The microstructure of the tube is austenite and grain boundary carbide, and the grain size is 8 grade. No twins and slip lines are observed. The microstructure at the elbow of the spare part is austenite and a small amount of carbide distributed along the grain boundary, and the twins and the slip line can be clearly observed.

---

![Figure 1. Microstructure of the burst tube](image1.png)

![Figure 2. Microstructure of the spare part](image2.png)

![Figure 3. SEM of the sample No.1-1. (a) low-magnification; (b) high-magnification](image3.png)

![Figure 4. EDS of the precipitates. (b) EDS of the precipitates on grain boundary of (a)](image4.png)

---

2.5 SEM and EDS analysis

The microstructure is further analyzed by SEM. Figure 3 shows the microstructure of the No. 1-1 sample with low-magnification and high-magnification. It can be seen that the precipitates are aggregated into a linear shape at the grain boundary. Figure 4 shows EDS of the precipitates. The results of EDS show that the precipitates are rich in Cr and Nb, which aggregate along the grain boundary.
3. Results and Discussion

The results of chemical composition analysis and mechanical property test at room temperature on the sample of the burst tube and the spare part show that the sample conforms to the requirements of ASTM A213/A213M on SA-213TP347H, which indicating that the chemical composition is normal. The operation time of the boiler is short, and no oxide layer is found on the inner and outer wall of the explosion position, and there are no signs such as bulging, bulging, etc., indicating that it is not caused by overheating \(^{[3]}\). There are excessive defects in the elbow, and the maximum ellipticity is 17%, which seriously exceeds the standard requirements. According to the requirements, the solution treatment should be carried out after the cold working of the elbow is completed. The solution treatment can reduce the residual stress and dislocation generated by the processing. The literature \(^{[3]}\) points out that the residual stress and the dislocations accelerate the precipitation of chromium in the grain boundary, the chromium boundary is sharply depleted, and the deformation-induced martensite potential is low, which seriously weakens the resistance of the grain boundary. As well, this high-temperature reheater elbow has not been solution treated after processing. Therefore, the unsolvent treatment after cold working is an important cause of high hardness on the sample of the spare part and the presence of more slip lines \(^{[6]}\).

Scanning electron microscopy and energy spectrum analysis show that there are precipitates of oxides and carbide particles with Cr and Nb at the grain boundary of the burst tube. Precipitates containing Cr are precipitated at the grain boundaries, which resulting in the formation of a chromium-depleted region at the grain boundaries, which deteriorates the corrosion resistance of the grain boundaries. The formation and development of chromium-depleted regions is controlled by the diffusion of Cr \(^{[5]}\). The large number of dislocations and vacancies generated during the cold processing of the elbows greatly promote the diffusion of elements. And the effect of deformation is accelerated sensitization for 18Cr-9Ni steel with carbon content of 0.04% or more. It is controlled by the diffusion of Cr and further accelerates the sensitization. It can be seen that the unsolvent treatment of the elbow severely reduces the corrosion performance of the grain boundary \(^{[6]}\).

In addition, the flue gas, coal ash contains chloride and excessive sulfide, sulfate, etc., may affect the solubility of oxides in the vicinity of the crack tip, thereby increasing the corrosion rate \(^{[7]}\). The literature \(^{[8-9]}\) shows that the main reason for the failure of austenitic stainless steel tubes is that sulfur element promotes grain boundary stress corrosion cracking. It can be seen that inclusions such as S can adversely affect the performance of the tube.

4. Conclusion

Based on the above analysis, one of the reasons for the frequent bursting of the high-temperature re heater is that due to the influence of the manufacturing quality, the defects in the bending process and the elliptic deformation exceed the standard, resulting in a decrease in the mechanical strength of the tube. Since the high-temperature reheater tube is not solution treated, the dislocations and residual stresses at the elbow increase, which accelerate the precipitation of the Cr element carbide at the grain boundary, and the grain boundary is sharply depleted in Cr, resulting in a decrease in grain boundary corrosion resistance. With the operation of the unit, the SA-213TP347H without solution treatment of the high-temperature superheater is frequently bursting under the combined action of steam pressure, thermal stress, residual stress and corrosive medium.

References

[1] Li, Z.L., Wang, J.A., Xiao, M.Y. (2015) Failure analysis of SA-213TP347H steel re heater tube. Heat Treatment of Metals., 40: 191-194.

[2] Ma, Q., Liang, P., Yang, S.E., et al. (2009) Investigation of high-temperature steam oxidation for TP347H steel. Transactions of Materials and Heat Treatment., 30: 172-176.

[3] Ma, G.B., Li, X.H., Xie, A.M. (2008) Short-time cracking analysis of TP347H tubes of high temperature heat delivery surfaces of boilers. Engineering Journal of Wuhan University., 40: 80-84.
[4] Tao, J., Yao, Z.J., Xue, F. (2006) Fundamentals of Material Science. Chemical Industry Press, Beijing.

[5] Wang, J.A., Li, J.P., Li, J. et al. (2015) Failure analysis of tube-burst of SA-213TP347H high-temperature reheater of 600 MW supercritical unit. Transactions of Materials & Heat Treatment., 36:122-127.

[6] Zhang, D.K. (1982) Local Corrosion of Stainless Steel. Science Press, Beijing.

[7] Long, H.G., Chen, H.D., Wan, K.Y. (2008) Failure analysis of high temperature superheater bend for boiler. Corrosion & Protection, 29: 157-159.

[8] Natesan, K., Kraus, C. (1998) Corrosion performance of structural alloys in oxygen/ sulfur/ chlorine-containing environments. In: 12th Fossil Energy Materials. Knoxville. pp. 18-30.

[9] Natesan, K., Baxter, D.J. Oxygen-sulfur corrosion of metals in mixed-gas atmospheres. In: 3rd Corrosion-Erosion Wear of Materials at Elevated Temperatures. Houston. pp. 67-86.