Failure analysis of a high temperature superheater pipe

Facai Ren¹, Jiansheng Su² and Xiaoying Tang¹

¹ Shanghai Institute of Special Equipment Inspection and Technical Research, Shanghai 200062, PR China
² Shandong Special Equipment Inspection Institute Co., Ltd, Jinan 250101, PR China

Corresponding author e-mail: caifaren@163.com

Abstract. The failure causes of a superheater pipe of a supercritical once-through boiler were analyzed based on the chemical composition analysis, tensile test, hardness and microstructure analysis. The results show that the microstructure changing from martensite to austenite due to the high temperature exceeded Ac1 causes the sharply decrease in the strength of superheater pipe.

1. Introduction

The superheater pipe is placed at the beginning of the flue gas path or at the bottom of the boiler. Failure causes of superheater pipe include design, material composition and inappropriate thermal operating conditions. Therefore, it is crucially necessary to identify the failure causes in order to prevent the similar accidents.

In the past, some researchers investigated the properties of different superheater pipes. Totemeier et al. [1] studied the fatigue crack growth behavior of ex-service experimental breeder reactor-II superheater duplex tubes. The results show that the retardation was caused by the disruption of crack planarity and uniformity after passing through the porous bond layer. Cicero et al. [2] investigated the failure cause of a superheater tube of a steam generator used in a dump. The results show that the fatigue processes were caused by the maintenance operation. Psyllaki et al. [3] investigated the short-time failure metallurgical factors of a pipeline during high-temperature operation. The results show that the material failed due to the rapid growth and coalescence of creep voids. Othman et al. [4] identified the possible root cause failure of the deformed superheater tubes using finite element method. The results show that the temperature was the main deformation factor due to restriction to the superheater tubes. Tavares et al. [5] discussed the causes of welded components cracks of chromium molybdenum alloy steels and presented the main recommendations. Sun et al. [6] proposed a new calculating tube wall temperature method based on the thermal deviation theory and local energy and mass balance of the superheater tube. The results show that the gas temperature field has a great influence on the final wall temperature calculation results.

In this paper, failure analysis on superheater pipe of thermal power plant was studied. The main cause of superheater pipe failure was determined.

2. Sample and Experimental

Before the pipe burst, the high temperature superheater had been running for about 25,000 hours. The steam pressure at the outlet of the high temperature superheater is 25.4 MPa and the steam temperature is 571 ℃. Samples were cut transversely from and around the burst opening and observed by
metallographic microscope. According to GB/T 13298-2015 < Inspection methods of microstructure for metals >, the microstructures were examined. According to GB/T 4336-2016 < Carbon and low alloy steel-Determination of multi-element contents-Spark discharge atomic emission spectrometric method (routine method) >, the chemical composition was analyzed by sampling 200 mm above the burst opening. The mechanical properties of the tensile specimens were analyzed from the pipe burst opening and far away from the burst opening.

3. Results and Discussions

3.1. Macroscopic morphology analysis
The burst macroscopic morphology of high temperature superheater pipe is shown in Fig. 1. It can be seen that the burst opening is plastic cracking and the opening is very large. The fracture surface is rough and uneven, and the edge of the burst opening is different in thickness. There are erosion marks on the inner surface of the burst pipe and obvious oxide scales on the outer surface of the burst opening. There is a macroscopically visible longitudinal crack on the inner surface of the oxide coating, which is caused by the instantaneous large deformation of the pipe. There is obvious bulging phenomenon in the straight pipe section with a length of about 1 m above the burst opening.

3.2. Chemical composition analysis
The chemical composition of high temperature superheater pipe is shown in Table 1. The chemical composition of the pipe meets the requirements of 10Cr9Mo1VNbN steel referring to GB/T 5310-2017 < Seamless steel tubes and pipes for high pressure boiler > or T91 steel referring to ASME SA-213 < Standard specification for seamless ferritic and austenitic alloy-steel boiler, superheater, and heat-exchanger tubes >.

Table 1 Chemical composition of high temperature superheater pipe (wt.%).

| Element          | C    | Si   | Mn   | Cr   | Mo   | V    | Nb   | P    | S    |
|------------------|------|------|------|------|------|------|------|------|------|
| Pipe             | 0.115| 0.331| 0.436| 8.428| 0.919| 0.183| 0.083| 0.0047| 0.0022|
| 10Cr9Mo1VNbN     | 0.08 | 0.20 | 0.30 | 8.00 | 0.85 | 0.18 | 0.06 | ≤    | ≤    |
| (GB/T 5310-2017) | ~0.12| ~0.50| ~0.60| ~9.50| ~1.05| ~0.25| ~0.10| 0.020 | 0.010 |
| T91              | 0.08 | 0.20 | 0.30 | 8.00 | 0.85 | 0.18 | 0.06 | ≤    | ≤    |
| (ASME SA-213)    | ~0.12| ~0.50| ~0.60| ~9.50| ~1.05| ~0.25| ~0.10| 0.020 | 0.010 |

3.3. Mechanical properties analysis
The tensile properties of high temperature superheater pipe is shown in Table 2. The test results show that the mechanical properties of the high temperature superheater pipe far from the burst opening zone and the burst opening zone meet the requirements of 10Cr9Mo1VNbN steel referring to GB/T 5310-2017 < Seamless steel tubes and pipes for high pressure boiler > or T91 steel referring to ASME SA-213 < Standard specification for seamless ferritic and austenitic alloy-steel boiler, superheater, and...
heat-exchanger tubes. But the hardness of the burst opening is close to the lower limit. The plastic elongation strength of the burst opening zone is very close to the tensile strength.

| Table 2 Tensile properties of high temperature superheater pipe |
|---------------------------------------------------------------|
| Sample                  | Yield strength (MPa) | Tensile strength (MPa) | Elongation (%) | Hardness (HBW) |
|-------------------------|----------------------|------------------------|----------------|----------------|
| Burst opening zone      | 598                  | 612                    | 23.5           | 190            |
| Non-burst opening zone  | 583                  | 644                    | 26.0           | 214            |
| 10Cr9Mo1VNbN (GB/T 5310-2017) | ≥415             | ≥585                   | ≥20            | 185～250       |
| T91 (ASME SA-213)       | ≥415                 | 585～796                | ≥20            | 185～250       |

3.4. Microstructure analysis

The metallographic microstructure of high temperature superheater pipe is shown in Fig. 2. Fig. 2(a) shows that the metallographic microstructure at the burst opening zone has completely changed from broken lath martensite to elongated ferrite + carbide. The martensite morphology has completely disappeared. The microstructure is oriented along the deformation direction. There are fewer carbides in the grain, more carbide particles at the grain boundary and creep microcracks. The metallographic microstructure at the burst opening zone has undergone phase transformation. It is inferred that the temperature of the pipe wall before burst has exceeded Ac1 temperature of T91 material. At this temperature, the material structure changes from martensite to austenite, and the strength decreases sharply, resulting in the superheated burst. After the burst, the temperature at the burst opening slowly decreases, and the metallographic microstructure changes from austenite to ferrite + carbide. As shown in Fig. 2(b), the microstructure of the pipe around the burst opening is ferrite + tempered martensite + carbide.

Figure 2. Metallographic microstructure of high temperature superheater pipe.

Microstructure far from the burst opening is shown in Fig. 3. The microstructure of the inner surface of the superheater pipe is tempered martensite, as shown in Fig. 3(a). Compared with the metallographic microstructure of the inner surface of the superheater pipe, the microstructure of the outer surface of the superheater pipe has changed into tempered sorbite, and the grain size has grown up. The number of carbides in the crystal is less. Most of the carbides gather at the grain boundary and are in the shape of chain sphere. This indicates that the temperature of the tube is higher during operation, and there is obvious temperature difference between the inner and outer surfaces, which leads to the difference of aging degree.
Endoscopic examination of the inlet header of high temperature superheater revealed that there were four foreign bodies in the inlet header, as shown in Fig. 6. The maximum length is about 60 mm. From the shape and color of foreign bodies, it can be inferred that they are metal flame cutting slag. During operation, if foreign bodies blocked the inlet header of the high temperature superheater pipe, the steam flow would be blocked and the pipe could not be effectively cooled, thus the pipe wall would be overheated.

4. Conclusion
In a short time before the burst, the temperature exceeds the Ac1 temperature of the material. The microstructure changes from martensite to austenite. The strength of the material decreases sharply. Under the action of internal pressure, the high temperature superheater pipe bursts, and a huge stress concentration is formed at the tip of the burst opening, which results in cracks at the upper and lower ends of the burst opening and extends outward.

References
[1] T.C. Totemeier, D.M. Wachs, D.L. Porter, N. Kisohara, Fatigue testing of metallurgically-bonded EBR-II superheater tubes, J. Nucl. Mater. 376 (2008) 38-46.
[2] S. Cicero, R. Lacalle, R. Cicero, J. García, Failure analysis of a steam generator superheater drain tube used in a dump, Eng. Fail. Anal. 17 (2010) 301-312.
[3] P.P. Psyllaki, G. Pantazopoulos, H. Lefakis, Metallurgical evaluation of creep-failed superheater tubes, Eng. Fail. Anal. 16 (2009) 1420-1431.
[4] H. Othman, J. Purbolaksono, B. Ahmad, Failure investigation on deformed superheater tubes, Eng. Fail. Anal. 16 (2009) 329-339.
[5] S.S.M. Tavares, J.M. Pardal, G.C. Souza, P.S.P. Garcia, E.S. Barbosa, C. Barbosa, I. Cardote Filho, Study of cracks in the weld metal joint of p91 steel of a superheater steam pipe, Eng. Fail. Anal. 56 (2015) 464-473.
[6] L. Sun, W.P. Yan, Prediction of wall temperature and oxide scale thickness of ferritic-martensitic steel superheater tubes, Appl. Therm. Eng. 134 (2018) 171-181.