Cause Analysis of Superheater Tube Cracking in Medium Temperature Separated Circulating Fluidized Bed Boiler

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Abstract. After running 41808 hours, the superheater tube of a medium temperature separated circulating fluidized bed boiler in a plant cracked. The tube is swollen and thick-lip-shape fracture is covered with oxides. By utilizing energy dispersive spectrometer (EDS), transmission electron microscopy (TEM), optical microscopy (OM), scanning electron microscopy (SEM), ANSYS, and other methods to detect the tube, it is found that the element content of the tube conforms to the standard. In terms of the shape of the fracture morphology, it is transcrystalline rupture, along with dimple and pores in the grain boundary. The carbides gather and grow at the grain boundaries, and the morphology of tempered sorbite is not obvious. By thermal field and stress analysis, the tube stressed runs in super-temperature environment. The tensile strength of the failed tube is not up to the standard. In all, the failure reason of superheater tube is high temperature creep cracking which is caused by the tube is not up to the T91 steel standard and long-term overheating resulted from the oxide layer.

1. Introduction
T91 steel possesses high strength and hardness, good creep rupture length at high temperature, good welding and processing properties [1], low thermal expansion coefficient and good thermal conductivity [2]. At present, it is widely used in advanced thermal power plants, especially in superheaters and reheaters [3]. Superheater is an important part of steam boiler. It has high temperature and high pressure steam inside and is scoured by high temperature flue gas outside [4]. The working environment is extremely bad [5]. When the superheater tube operates at high temperature and high pressure for a long time, the material of the tube will deteriorate [6]. The microscopic manifestations are pearlite spheroidization, redistribution of alloy elements, aggregation and growth of carbides at grain boundaries [7]. At the same time, the tensile strength, durable strength and creep properties will decrease obviously with the decrease of the structure and properties [8].

The material is taken from the superheater failures tube of a factory's medium temperature separation circulating fluidized bed boiler. The tube runs for 41808 hours. Its material is T91 and the size is Ø32 mm×5mm. The medium inside the tube is high pressure steam with pressure of 9.8 MPa and temperature of 545℃ and the medium outside the tube is boiler flue gas. The inlet temperature is 760±50℃ (the temperature measuring point is about 3.5 meters away from the crack of the tube) and the outlet temperature is 740±50℃. Through test analysis, it is found that the failure causes of superheater tube.
2. Test analysis

2.1. Macro-analysis
Macroscopic examination of cracked tube shows that the oxidation colour of the surface of the failed tube is different from that of the non-failed tube, and the oxidation of the obviously failed tube is more serious. The diameter of the uncracked part of the failed tube is 33.1 mm, and the diameter of the uncracked tube is 32.3 mm. As sketched in figure 1, the failure tube has undergone uniform expansion and large deformation. From the macro-morphology of the cracked tube in figure 2, the crack has obvious plastic deformation and outward turn and its surface is thicker oxide layer. The crack is rough and open to both sides and the edge is uneven and blunt. The longitudinal crack on the outer wall of the tube near the crack is consistent with the direction of the crack. Thick oxide layer is on the inner and outer walls. The oxide layer thickness at the corresponding rupture position of the tube is obviously larger than that at the other parts.

![Figure 1](image1.png)
Figure 1. Comparisons of the diameters of failed (left) and non-failed (right) tubes

![Figure 2](image2.png)
Figure 2. Macro-morphology of cracked tube

2.2. Chemical composition analysis
The chemical composition of cracked tube is analyzed by energy dispersive spectrometer. The test method is in accordance with GB/T223 standard. The results of analysis (mass fraction) are shown in Table 1. The content of each element basically meets the GB 5310-1995 standard.

| Element | Standard values | Measured value |
|---------|-----------------|----------------|
| C       | 0.08-0.12       | 0.10           |
| Mn      | 0.30-0.60       | 0.41           |
| Si      | 0.20-0.50       | 0.43           |
| Cr      | 8.0-9.5         | 9.76           |
| Mo      | 0.85-1.05       | 0.73           |
| V       | 0.18-0.25       | 0.18           |

Table 1. Chemical composition and analysis results of superheater materials(wt%)

2.3. Feature analysis
The fracture morphology is observed by scanning electron microscopy, and transgranular cracking is found on the whole fracture surface as shown in figure 3 (a). The inner surface has obvious dimples as shown in figure 3 (b). The thickness of the oxide layer on the inner surface of the tube is about 0.1 mm as shown in figure 3 (c) and that on the outer surface of the leeward side is about 0.3 mm as shown in figure 3 (d).
2.4. Metallographic analysis

The metallographic structure of the windward section of the failure tube and the section of the non-failure tube are observed by optical microscope. The metallographic morphology of the windward section of the failure tube and the section of the non-failure tube is shown in figure 4. In the section of the non-failure tube, the structure is normal tempered sorbite in figure 4(b), while in the failure tube, the morphology of tempered sorbite is not obvious and there is a tendency of carbide aggregation and growth in figure 4(a).
Scanning electron microscopy (SEM) is used to analyze the outer surface of the cracked tube. As shown in figure 5, grain boundaries and grains have obvious carbides, and no lath structure is observed. This phenomenon would lead to the decrease of material properties.

![Scanning electron microscopy images](image)

Figure 5. Analysis of the outer surface of the cracked failure tube

2.5. Thermal field analysis

The ANSYS software is used to simulate and analyze the heat field of the tube. The simulation parameters are set as follows: the outer diameter of the tube is 32 mm, the thickness of the anti-wear tile was 5 mm, and the material is the same as the tube; the inlet of the flue gas was 15 m/s, and the temperature is 1033 K; the heat transfer coefficient of the steam convection in the heat exchange tube is 2300 W/m²·k; and the thermal conductivity of the T91 material is set 30 W/m·K and the specific heat capacity is 740 J/kg·K. It is considered that the thermal resistance of the contact surface between heat exchanger tube and tube bush is equivalent to that of P/T91 steel plate with 25mm thickness. There is an initial gap between the wear-proof tile and the tube, and the contact between the two after a period of use.

As shown in figure 6, the simulation results show that when the tube is not in contact with the anti-wear tile, the maximum temperature of the outer surface of the tube is 592°C and the minimum temperature is 572°C. The highest temperature of the inner surface is 580°C and the lowest temperature is 565°C. When the tube is in contact with the anti-wear pad, the cracking position has a local high temperature, and the temperature is 610°C, and the other temperature is about 585°C. Local high temperature zone exists in the cracking location, which is nearly 25°C higher than other locations. In the test, the contact thermal resistance between the anti-wear pad and the tube is assumed, and the temperature of the outer wall of the anti-wear pad may deviate from the reality.

![Simulation results](image)

(a) (b)
2.6. Stress analysis

The outer diameter of the tube is 32 mm, the inner diameter is 22 mm and the internal pressure is 9.8 MPa. The bending and temperature stress are not considered. The material parameters are that elastic modulus is 130 GPa, Poisson's ratio is 0.3Norton function is used to construct the formula $\dot{\varepsilon}_c = B\sigma^n$, $B$ is 1.21E-10, $n$ is 1.95[9]. Creep time is 42000 hours. Stress distribution before and after creep is shown in figure 7, and creep deformation after creep is shown in figure 8. The stress and deformation of the tube are not high. The $\lg\sigma$-P$_L$-M curve obtained from the data of the durability of T91/P91 steel can be fitted as [10]:

$$\lg\sigma = 3.1083 - 0.0237\exp(0.1493P_L - M)$$

The formula can predict that the maximum stress of T91 steel is about 80MPa when it runs for 42000 hours at 610℃. When the flue gas temperature is 810℃, the maximum temperature at the crack site of the tube will not exceed 660℃ (simple superposition of 50℃), and the maximum stress corresponding to the 42000 hours operation of the tube will be 43 MPa.

The tube is not subjected to obvious bending stress during operation and the creep failure of the tube will not occur if the material of the tube meets the requirements of T91 steel standard.
2.7. Tensile test

According to ASME BPVC standard, the tensile strength and yield strength of T91 at room temperature should meet 585 MPa and 415 MPa. Tensile specimens are taken from the non-cracked parts of failed and non-failed pipes, and tensile tests are carried out at room temperature until fracture. The drawing curve is shown in figure 9 and the drawing results are shown in Table 2.

![Tensile test curve](image)

**Figure 9. Tensile test curve**

| Standard value | Yield strength (MPa) | Tensile strength (MPa) | Elongation (%) |
|----------------|----------------------|------------------------|----------------|
| Measured value of failure tube | 247 | 443 | 22.0 |
| Measured value of normal tube | 426 | 637 | 10.5 |

3. Discussion on test results

The macro morphology is analyzed. The crack of the tube is a shear-lip blasting, with the crack turning out, the surface of which has a thick oxide layer, the edge of the crack has uneven blunt edges, and the outer wall of the nearby tube has longitudinal cracks consistent with the direction of the crack. The inner and outer walls of the tube have a thick oxide skin near the break.

As shown in the cross section of the tube, the oxide layer thickness at the corresponding rupture position of the tube is obviously larger than that at the other parts. These characteristics are typical macroscopical characteristics of long-term high temperature overheating of tubes.

The fracture morphology is analyzed. During the fracture, obvious plastic deformation occurred, transgranular cracking appeared on the whole fracture surface, and dimples are found on the inner surface of the fracture. The transgranular cracking and dimple characteristics of the fracture surface are the typical micro-fracture characteristics of the long-term high temperature overheating of the tube.
The metallographic structure is analyzed. The energy spectrum analysis shows that the composition of the tube basically meets the requirements. During the metallographic analysis, the metallographic structure of the failure tube is quite different from that of the non-failure tube. Grain boundaries and grains have obvious carbides, and the carbides have obvious tendency to aggregate and grow. The above metallographic structure characteristics are typical metallographic structure characteristics of the tube during long-term high temperature superheating operation.

The thermal stress is analyzed. According to the finite element analysis and stress analysis of tube, the cracking location has a local high temperature zone, which is nearly 25°C higher than other locations. The tube has been in high temperature for a long time. The creep failure of the tube will not occur after calculation if the tube meets the requirements of T91 steel standard. It can be preliminarily inferred that the pipeline tube has some problems.

The tensile test is analyzed. According to the analysis of mechanical properties and tensile tests, the material properties of the failed tube not up to the standard requirements. The yield strength of the failed tube is nearly 170 MPa different from the standard requirements, which is also one of the reasons for the failure of the superheater tube.

In summary, the failure reason of superheater tube is high temperature creep cracking which is caused by the tube is not up to the T91 steel standard and long-term overheating resulted from the oxide layer.

4. Conclusions
The failure reason of superheater tube is high temperature creep cracking which is caused by the tube is not up to the T91 steel standard and long-term overheating resulted from the oxide layer. It is suggested to control the composition of the tube and minimize the formation of oxide layer in order to ensure the reliable operation of the superheater. Due to the existence of oxide layer, the diameter of the failed tube will increase. The wall thickness of the tube in key parts can be measured regularly, the troubled tube can be cleaned or replaced in order to ensure the safe operation of the equipment.

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