Failure Analysis of Superheater Boiler Tube SA 213 T12

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Abstract. Superheater tubes SA213 T12 (OD = 57 mm, WT = 6 mm) has been in service for 11 years in a supercritical coal fired boiler (315 MW). Tubes operating temperature are 430°C and pressure is 11 MPa. Failure occurred on tube no. 20, row 2. Three tubes specimens from the same row (failed tube, tube no. 3, and no. 4), were drawn for laboratory examinations. Vickers microhardnesses of failed and no. 3 tubes are the same (140 VHN), while tube no. 4 hardness is 170 VHN. These hardness values are much lower compared to the new tube (192 VHN). The lower hardness value of failed tube is due to complete decomposition of pearlite colonies in inner and outer side of failed tube to ferrite and spheroidized cementite. Failure of tube is characterized by thin lip rupture which indicated that the tube circumferential deformation occur gradually following spheroidization process. Failure by intergranular crack occurred along grain boundaries when the stress on the tube wall (hoop stress) exceeding material strength at service temperature. Tube no. 3 and 4 are partially spheroidized, mostly on the insideside. The severity of microstructure damage is related to the flow direction of flue gas, from tube no. 1 to no.2, no.3 and so on. Tube no. 1 was survived because it was protected by a front cover that will limit heat transfer from the flue gas. The previous failure analysis of similar boiler tube revealed that the hardness of the bulging tube is about 140 VHN which is the same as the hardness of the failed tube (no. 2) and no.3. Tube no. 3 is in the early stage of damage and shall be replaced because the hardness is much lower than 170 VHN. The effect of flue gas flow direction not only affects the hardness and microstructure but also deposit thickness. Deposit thickness in tube no. 2, 3, and 4 are 149, 123, and 100 µm respectively. Thicker deposit in tube no. 2 is also contributed to premature failure of this tube compared to the others. The local temperature of tube wall will be higher because thick deposit will reduce heat transfer between flue gas and steam inside the tube.

Keywords: SA213 T12, superheater tube, creep damage, spheroidization, deposit thickness

1. Introduction

Superheater tube is one of important components in the power boiler system. Steam for power generation was produced by heating the tube containing water or steam by flue gas from the burning coal. Due to their nature of service, superheater tube will be exposed to high temperature and coal debrises during service. Failure of superheater tube might occur when it has been exposed continuously to high temperature for long period
of time. Several failure mechanisms might occur to the tube, such as creep, spheroidization, graphitization, overheating, and wear [1]. Creep is time-dependent degradation of material under stress and high temperature. Creep damage can be identified through several characteristics such as long exposure time, thick crack lip, microvoids, and intergranular crack. Spheroidization of cementite is another type of high temperature failure that arises from decomposition of pearlite into ferrite and spherical cementite that will reduce material strength substantially. Spheroidization occurs above 600°C and can be identified by disappearance of perlite colonies in microstructure. Similar to spheroidization, graphitization is degradation due to decomposition of pearlite into ferrite and graphite at a temperature lower than 600°C followed by intergranular crack along graphite sites on the grain boundaries [2]. This paper will present the root cause analysis of repetitive failure of superheater tube in a 315 MW coal fired boiler. First failure was found in 2014 [3], and recent failure in 2018 (after 11 years of service). Superheater tube operating temperature is 430 °C and pressure of about 11 MPa.

2. Materials and Methods

Superheater tube material is ASME SA213 T12, outer diameter and thicknesses are 57 and 6 mm respectively. Three tube samples were drawn from tube no 20; row 2, 3, and 4 (Figure 1). Tube row 2 is the failed tube and tubes row 3 and 4 are un-failed tubes near row 2. Superheater tube material identification was carried out by chemical analysis, tensile test, microhardness test, and microstructure analysis. Chemical compositions of each tube were examined using optical emission spectroscoppe ARL 3460. Tensile tests were conducted using 20 tonnes Tarno Grocky universal tensile testing machine. Hardness tests were conducted using Zwick Digital Vickers Microhardness Tester at 600 gram load. Microstructures were observed using Nikon Eclipse MA2000.

2.1. Tube Material Properties

![Image](image1.png)

**Figure 1.** Pipe samples for laboratory examinations

3. Results and Discussion

3.1. Tube Material Properties
The average results from three examinations of chemical compositions on each tube sample and their comparison to ASME and China (GB) Standards are shown in **Table 1**. Chemical compositions of ruptured and unfailed tubes fulfil 12Cr1MoV specification.

**Table 1. Chemical Composition (weight %) of Tubes**

| Element  | Testing Results | Specifications [4, 5] |
|----------|-----------------|-----------------------|
|          | Ruptured No. 20 row 2 | Unfailed No. 20 row 3 | Unfailed No. 20 row 4 | ASME SA213 T12 Specs. | GB 8162 12Cr1MoV Specs. |
| C        | 0.12            | 0.14                 | 0.14                 | 0.05 - 0.15           | 0.08 - 0.15 |
| Si       | 0.19            | 0.20                 | 0.19                 | ≤0.50                | 0.17 - 0.37 |
| P        | 0.0035          | 0.0050               | 0.0049               | ≤0.025               | ≤0.035       |
| S        | 0.013           | 0.021                | 0.019                | ≤0.025               | ≤0.035       |
| Mn       | 0.56            | 0.56                 | 0.54                 | 0.30 - 0.61          | 0.40 - 0.70 |
| Ni       | 0.061           | 0.044                | 0.043                | ---                  | ≤0.30        |
| Cr       | 0.93            | 0.95                 | 0.94                 | 0.80 - 1.25          | 0.90 - 1.20 |
| Mo       | 0.28            | 0.30                 | 0.29                 | 0.44 - 0.65          | 0.25 - 0.35 |
| V        | 0.19            | 0.18                 | 0.18                 | ----                 | 0.15 - 0.30 |
| Cu       | 0.16            | 0.13                 | 0.12                 | ----                 | ---          |
| Fe       | Balance         | Balance              | Balance              | Balance              | Balance      |

Tensile test was carried out according to ASTM A 370 standard. Result of tests and its conformation to ASME and GB standard is shown in **Table 2**. Tensile strength of failed tube (No. 20 row 2) is much lower compare to that of unfailed tube but slightly above minimum requirement. The lower value of tensile strength is due to material degradation after long time exposure; but the yield strength is still above specification. Tensile and yield strengths of two good tubes (No. 20 row 3 and 20 row 4) are still fulfils ASME SA213 T12 and GB specification [3,4].

**Table 2. Tensile Properties of Tube**

| Properties          | Testing Results | Specifications [4, 5] |
|---------------------|-----------------|-----------------------|
|                     | Failed Tube No. 20 row 2 | Unfailed Tube No. 20 row 3 | Unfailed Tube No. 20 row 4 | SA213 T12 | GB 8162 12Cr1MoV |
| Tensile Strength, MPa | 474              | 542                   | 567                   | ≥415      | 470 - 640        |
| Yield Strength, MPa | 349              | 418                   | 412                   | ≥205      | ≥255             |
| Elongation, %       | 39               | 34                    | 30                    | ≥30       | ≥21              |

**Table 3. Hardness Test Result**

| Sample                  | Average Hardness (VHN) | SA213 T-12 Specification [4] |
|-------------------------|------------------------|-----------------------------|
| Hardness data in December 2017 |                        |                             |
| Tube No. 20 row 2        | 1.40                   | ≤ 170                       |
| Tube No. 20 row 3        | 1.41                   |                             |
| Tube No. 20 row 4        | 1.70                   |                             |
| Hardness data (mid-thickness) in June 2014 |                     |                             |
| Good Tube No. 10.4       | 1.92                   |                             |
| Bulging Tube No. 12.4    | 1.39                   |                             |

The hardness of tubes in row 2 (failed) and 3 (un-failed) are below specification. The lower values of hardness indicated that the material properties have been degraded. The hardness of tube row 4 (un-failed) is in the lower specification limit. The current result will be compared to the previous data taken in June 2014 of the new and bulging tubes. The hardness of new tube is 192 VHN and the bulging one is 139 VHN. It is clear that the hardness of 140 VHN of un-failed tube (row 3) is close to the hardness of the bulging tube, therefore this tube shall be replaced to prevent unexpected
failure during service. The hardness value of 140 VHN can be used as reference for tube replacement.

Microstructure examinations will be conducted to verify the degree of degradation in material by observing the status of pearlite in microstructure. Microstructures of tubes were taken from the longitudinal section of the failed tube (row 2), and two good tubes (row 3 and 4). Specimen of the failed tube was taken from location far from the bursting part (near one of the edge in Figure 1a).

**Figure 2** shows the microstructure of tubes at the mid-thickness. The microstructure of good tubes (**Figure 1b** and **c**) consists of ferrite and pearlite. Pearlite structures are partially degraded but still present. Pearlite phases in failed tube have been decomposed completely (**Figure 1a**) to ferrite and spheroidized cementite. **Figure 3a** shows the optical micrograph of failed tube at high magnification. Some microvoids on grain boundaries are evident (arrow signs). Scanning electron microscope (SEM) examination was also performed on the same sample to obtain a clearer picture of microvoids on the grain boundaries.

**Figure 2-4** shows the comparison of microstructure of the tubes inner surface. It can be seen in **Figure 4** that the failed tube has the thickest deposit among them. The damage in pearlite structure will occur in shorter time with increasing deposit thickness because of higher local temperature.

![Figure 2. Optical micrographs of tubes at mid thickness](image-url)
3.2. Failure Mechanism

Tube shows a thin lip rupture types of failure. Thin lip rupture is a characteristic of stress rupture failure that was initiated by bulging. Bulging itself is a time dependent process where spheroidization process decreased material strength gradually. Rupture occurred when the stress on the tube wall (Hoop stress) is higher than material strength at temperature. Microstructure of failed tube has been examined to obtain data about microstructure degradation and crack propagation mode. Two locations were observed, near the fractured lip and its opposite side (180° from the fractured lip).

Figure 5 shows the microstructure of failed tube at the fractured lip. Figure 5a shows the remaining deposit on the inner surface, most of the deposit has been wiped out by the steam flow during rupture. Crack propagation along grain boundaries (intergranular
crack) are shown in Figure 5b to d. Intergranular cracks occurred along the grain boundaries. It can also be seen that pearlite structure vanished completely due to spheroidization process (Figure 5d).

Figure 6 shows the microstructure at the opposite of the crack (180° from the crack lip). There is no intergranular cracks found on the mid-thickness section, however the pearlite structure also disappear completely by spheroidization process (Figure 6d).

Hardness of pipes at the fractured lip and its opposite side have been examined using Vickers microhardness to confirm the degradation of microstructure because the damage or transformation of pearlite into ferite and graphite will decrease the hardness significantly. The average hardness of fractured lip is 130 VHN and the opposite side is 152 VHN. The lower hardness near the fractured lips confirmed the effect of microstructure degradation to decrease the hardness and strength.

Figure 5. Microstructure at the cracked tube

Figure 6. Microstructure at the opposite of the crack

a. Inner surface
b. Inner surface, fractured lip
c. Mid-thickness
d. Mid-thickness at higher magnification

a. Inner side
b. Outer side
4. Conclusions

Failure of low temperature superheater tube is caused by spheroidization after about 11 years of service. Spheroidization damage in tube No. 20 row 2 has been accelerated by the present of thick deposit on the inner side. Observation of deposit thickness revealed that tube No. 20 row 2 has the thickest deposit compared to that of tube No. 20 row 3 and 4. Thicker deposit will promote higher local temperature because deposit will decrease the heat transfer between flue gas and steam.

The tube rupture is related to the microstructure damage by mean of pearlite tranformation to ferrite and carbides and followed by the decrease in hardness. Pearlite colonies in tube No. 20 row 2 has completely damaged and the hardness decrease to 140 VHN which is the same as the hardness of the bulging tube (previous failure in 2014). Microstructure of pipe No. 20 row 3 also affected and the hardness decreases to 141 which indicate that this material is entering the early stage of creep and shall be replaced immediately to prevent unexpected failure. Microstructure of pipe No. 20 row 4 was not affected significantly and the hardness of 170 is far above the bulging hardness. The current findings of tube hardness (140 VHN) which is supported by previous case (failure in 2014) can be used as reference hardness for tube replacement without conducting time consuming destructive test.

5. Acknowledgements

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6. References

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