Water wall tubes failure analysis in a 25-megawatt steam power plant

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Abstract. The failure of water wall tubes in a boiler steam power plant has been analysed. When the first inspection was conducted on the 25-Megawatt steam power plant, leakage was found on several water wall circulating fluidized boiler (CFB) tube. Visual examination, chemical composition analysis, hardness measurement, and metallographic examination on the tube samples cut from the water wall were used to analyse the cause of the failure. Visual examination showed that there is a thick weld joint on the tube inner side that could induce overheat and cause the tube to fracture and, in some locations, there were thick deposits on the tube inner side. A Hardness measurement of the tube near the fracture location showed an increase in the hardness value ranged from 191 – 206 HV. Metallographic examinations showed that there has been some micro-crack along the grain boundary. Composition analysis on the deposit at the inner side of the tube showed a trace of magnesium and calcium indicate that the water quality of the boiler doesn’t meet the standard. To resolve the problem, it is recommended to fix the weld procedure and kept the water quality to meet the standards.

1. Introduction
Due to its fuel flexibility that could fire fossil fuel, biofuel, solid waste and low local pollutant emission, circulating fluidized bed (CFB) boiler technology had been utilized in many industries and the utilization has grown exponentially since the early 1980s [1]. The disadvantages of using this technology are the tube material degradation at the in-bed heat exchanger component [2].

Failure in boiler tubes is one of the common phenomena that cause unscheduled outage because it operates at the condition of high pressure and temperature of steam and water. Srikanth et al., presented in their study the failure of a water wall tube that has a mild whitish deposit and multiple fine cracks at the water-side of the tube and thin-lipped crack at the fireside [3]. The cause of the failure presented was localized caustic corrosion followed by phosphate induced intergranular stress corrosion cracking due to the presence of some excess amount of sodium phosphate in the feed water. Kain et al., studied the cause of a few super heater tube leakage failures was due to high oxidation at localized regions followed by spalling of the oxides at high operating temperature and high velocity of bed particle of the fluidized bed [4]. For waste fired boilers there is some operational problem like high-temperature corrosion of water walls which limit the steam value and boiler efficiency due to the existence of ash forming elements such as Cl, Br, Zn and Pb that induced the corrosion as shown at Vainikka et al study [5]. Prabu et al., showed in their evaluation of water wall tube failure with fish-mouth appearance along the longitudinal direction of the tube and an excessive wall thinning near the bulging area are failed due to short time overheating which occurred at the temperature between AC1 and AC3 line because the
microstructural observed on the failed tube area was Widmanstatten ferrite [6]. In another study, Xiaohe et al., investigate the high-temperature corrosion in CFB super heater which found sodium sulfate and sodium chloride salt at the corrosion product covering the super heater tube surface and conclude that the sodium sulfate was the major corrosion culprit suggesting the need for reducing the sulfur content from the fuel or using spray coating technology to mitigate the problem [7]. In the study done by Xue et al [8], their study found excessive sodium hydroxide at water wall boiler area that failed and their analysis concluded that the failure is caused by corrosion-induced failure from the excessive natrium hydroxide at the boiler water and the corrosion can proceed continuously causing water wall tube thinning. Another analysis was done by Chengchuan et al., in a leaked water wall tube with tube thinning, decarburization at the fracture and intergranular cracks on the inner wall concluded that the cause of the failure was hydrogen corrosion [9].

In this study, leakage failures of a water wall tube of a CFB boiler power plant were analyzed. The CFB boiler power plant consists of two units with a rated capacity of 2 x 25 MWe and 120 tons of steam/hour at 99 kg/cm². The plant had operated since 2012 and utilize lignite coal as its fuel. Leakage failure on the boiler water wall tube was found when the first inspection was conducted at unit number 2. Failed water wall tube sample from the boiler was sent to the laboratory to be examined to find out the cause of the failure. The super heater tube design was made of SA210-grade seamless carbon steel tube. The water wall tube working environment was designed with a water temperature of 318 °C and the average furnace flue gas temperature of 873 °C. The thickness of the tube is 5 mm and the outer diameter is 51 mm.

2. Method
The location of the water wall tube and the layout of the boiler are shown in Error! Reference source not found.. The failed tubes are then cut from the boiler and two samples A and B of the failed water wall tubes in this investigation are sent to the laboratory to be analyzed.

![Figure 1](image)

**Figure 1.** (a) Boiler layout and the water wall tube location (not drawn to scale) (b) failed water wall tube.

The visual macroscopic examination was done by taking photographs using a digital camera. The tube samples were then cleaned, inspected visually and the thickness was measured. The tube sample cut was mounted then polished using the conventional technique by using a metallographic grinding machine and etched using 2% Nital to observe its microstructure using the BX51M-Olympus optical microscope.
and Hitachi-TM3000 scanning electron microscope (SEM). The hardness of the samples was then measured using a Vickers hardness tester machine with a load of 5g. Chemical composition of the samples was tested by PMI Master Pro and the deposits of corrosion products of the tube were tested for its chemical composition using energy dispersive spectroscopy (EDS).

3. Results and discussion

3.1. Visual examination

The samples from the failed tubes were then cut longitudinally and the visual appearances are shown in Figure 2 and Figure 3. Visual examination on sample A showed “fish mouth” appearance with the thinned section at the failed area and there is a weld joint at the inner side with excessive root penetration. The fish mouth appearance indicates that the tube was failed because of a short time overheating [6,10], which caused by unstable or turbulence water flow. The weld joint would disrupt the water flow which could cause local heating resulting in higher material operating temperature and damage to the tube.

**Figure 2.** Photographs of tube sample A (a) inner side and (b) outer side (c) detailed view of weld joint at inner side of the tube and (d) detailed view of thinned section at the leakage.

In sample B visual examination showed there are two cavity leaks at the tube and there is a weld joint at the inner side of the tube. In the area surrounding the cavity it can be seen corroded surface. The thinned section surrounding the cavity show that the tube locally thinned from the outer side indicate that the leak from the sample A burst to the sample B surface.

**Figure 3.** Photographs of tube sample B (a) inner side and (b) outer side (c) detailed view of weld joint at inner side of the tube and (d) detailed view of thinned section at the leakage.
3.2. Composition analysis
The chemical composition of the failed tube was checked and compared with corresponding standard 20G steel according to the manufacturer drawing. The data is shown in Table 1 and it can be seen that the material complied with the standard.

**Table 1. Chemical composition (wt. %) of the sample.**

| Elements (wt.%) | C  | Mn  | P    | S     | Si  | Fe    |
|----------------|----|-----|------|-------|-----|-------|
| Tube sample    | 0.22 | 0.508 | <0.005 | <0.003 | 0.266 | Balance |
| 20G steel      | 0.17 - 0.24 | 0.35 - 0.65 | < 0.030 | < 0.030 | 0.17 - 0.37 | Balance |

3.3. Thickness measurements
The measurements of the thickness in position as shown in [Figure 4](#) and [Figure 5](#) were taken across the sample and the results are presented in **Table 2** and **Table 3**.

**Figure 4.** Thickness measurement position of sample A.

**Table 2.** Thickness of sample A.

| No | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|----|---|---|---|---|---|---|---|---|---|----|----|----|
| Thickness (mm) | 4.79 | 4.69 | 4.43 | 5 | 4.65 | 4.59 | 3.46 | 3.13 | 2.85 | 3.37 | 1.85 | 2.95 |

It can be seen that the thickness at the area of the rupture (position 7 – 12) in sample A are smaller than the area before the weld joint (position 1 – 6) and in sample B the thickness of the tube also indicates a not similar thickness of the tube across the weld joint that is position 1 - 9 compared with position 10-12.

**Figure 5.** Thickness measurement position of sample B.

**Table 3.** Thickness of sample B.

| No | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|----|---|---|---|---|---|---|---|---|---|----|----|----|
| Thickness (mm) | 2.45 | 2.94 | 2.69 | 2.47 | 2.69 | 2.58 | 4.36 | 2.24 | 3.66 | 4.19 | 3.98 | 4.05 |
3.4. Microhardness measurements

Microhardness measurement was carried on the tube sample at the location near the rupture and at the parent metal as shown in Table 4. The average hardness at the location near the rupture (192 HV) is higher than the parent metal (136 HV). The increase in microhardness value at the rupture area could be because of the formation of bainite due to the overheating followed by the rapid cooling of the tube sample by the escaped water/steam through the ruptured tube [10].

Table 4. Hardness measurement of tube sample.

| Measurement          | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | Average |
|----------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|---------|
| Near Rupture (HV)    | 191 | 193 | 176 | 189 | 199 | 177 | 202 | 190 | 196 | 206 | 192     |
| Parent Metal (HV)    | 135 | 134 | 137 | 138 | 138 | 135 | 131 | 134 | 136 | 139 | 136     |

3.5. Metallographic examination

Metallographic examination of the etched sample was carried to know if there is an abnormality in the microstructure of the failed tube and shown in Figure 6. The microstructure of the metal showed ferrite – pearlite structure Figure 6.b. At the inner and outer side of the tube it can be observed that that the surface of the metal has been corroded (Figure 6a and 6c) and there are microcrack at the middle side of the tube (Figure 6b).

Figure 6. Optical micrograph of the failed tube (a) at inner side showing oxide layer (b) middle side shows ferrite-pearlite structure and there is a microcrack and (c) outer side showing oxide layer.

3.6. Deposit examination

The deposit that formed at the surface of the tube was scrapped and then being examined using SEM and EDS to find out what kind of elements contained in the deposit. The maximum oxide thickness observed was 367 µm at the inner tube section as shown in Figure 7b and from its chemical composition the deposit showed that it contains magnesium, manganese, and calcium (Figure 7c) which indicate poor quality of the water-steam of the boiler.
Figure 7. SEM and EDS result of the sample. (a) Deposit at the inner tube (b) maximum oxide thickness and (c) Elements detected on the tube oxide.

4. Conclusion and recommendation
Failure analysis showed that the failed tube sample complied with the standard. The findings on the examination of the failed water wall tube with thin lip fish mouth opening indicate that the tube was experiencing short time overheating which could be caused by unstable flow due to the excessive root penetration at the weld joint. The analysis on the oxide layer of the outer and inner tube oxide showed a trace of magnesium and calcium which indicate improper water quality of the boiler. To resolve the problem, it is recommended to fix the weld procedure and kept the water quality to meet the standards.

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