Metallurgical Analysis of Cracks Formed on Coal Fired Boiler Tube

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Abstract. Metallurgical failure analysis was carried out for cracks observed on the outer surface of a boiler tube made of ASME SA 210 GR A1 grade steel. The cracks on the surface of the tube were observed after 6 months from the installation in service. A careful visual inspection, chemical analysis, hardness measurement, detailed microstructural analysis using optical and scanning electron microscopy coupled with energy dispersive X-ray spectroscopy were carried out to ascertain the cause for failure. Visual inspection of the failed tube revealed the presence of oxide scales and ash deposits on the surface of the tube exposed to fire. Many cracks extending longitudinally were observed on the surface of the tube. Bulging of the tube was also observed. The results of chemical analysis, hardness values and optical micrographs did not exhibit any abnormality at the region of failure. However, detailed SEM with EDS analysis confirmed the presence of various oxide scales. These scales initiated corrosion at both the inner and outer surfaces of the tube. In addition, excessive hoop stress also developed at the region of failure. It is concluded that the failure of the boiler tube took place owing to the combined effect of the corrosion caused by the oxide scales as well as the excessive hoop stress.

Keywords: Boiler tube, Crack, Ash corrosion, Hoop stress, EDS, SEM

1. Introduction
Failure of boiler tubes is common in industries where fossil fuel is used. There are several factors that cause this type of failure. The use of high sodium, sulphur and ash containing fuel, high working temperature and pressure exceeding the design limit and lack of periodic maintenance are the major factors that affect the performance of materials employed for boilers [1, 2]. The hostile environment is the source of corrosion and stress which leads to the failure of boiler tube. The failure of boiler tubes appears in the form of bending, bulging, cracking, wearing or rupture and these hampers the performance of boilers or makes it obsolete in applications [3].

In most of the cases ash corrosion is found to be the prime factor for failure of boiler tubes. This ash corrosion occurs basically due to use of low quality feed coal as fuel and poor cleaning procedures. In these types of failure ash deposition takes place on the fire side of the boiler which provides excessive heat input and leads towards failure while in other cases, accumulation of corrosion products takes place which induces localized corrosion on waterside of the boiler [4]. In the present investigation a systematic case study of the boiler tube failed in Welspun India plant located at Anjar is presented.

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2. Experimental procedure
A boiler tube of ASME SA 210 GR A1 grade was taken for the present investigation. The detailed parameters used during its application are summarized in Table 1. In order to find the root cause several analyses were carried out. This includes visual inspection, chemical composition analysis, hardness testing, microstructural characterization using optical microscopy and scanning electron microscopy (SEM) coupled with energy dispersive X-ray spectroscopy (EDS).

| Parameters                  | Range                        |
|-----------------------------|------------------------------|
| Dimension of Tube           | 50.8 mm OD & 6.35 mm WT      |
| External temperature        | 700-800 °C                   |
| Internal temperature        | 250-295 °C                   |
| Pressure                    | 50-80 kg/cm²                 |
| TDS of water used in boiler | 400-700 ppm                  |
| pH of water used in boiler  | 8.5                          |
| Quality of coal on GCV scale| 4000                         |
| Duration of failure         | 6 months                     |

Visual analysis was the first step and for it photographs of the cracked region of the boiler were taken. Thickness of the tube at cracked region and away from the failed region was measured using digital micrometer. The chemical analysis of the failed tube was performed using optical emission spectrometer. Hardness measurement at the failed region and away from the failed position was carried out using Rockwell hardness. A small specimen was taken from the failed region and it was then prepared for microstructural observation following conventional polishing and etching. The microstructures were taken using optical microscope at several positions. The morphology and chemical analysis of the deposits on the tube were checked by SEM and EDS.

3. Results and discussion
3.1 Visual inspection
Careful visual inspection of the failed tube revealed the presence of oxide scales and ash deposits on the surface of the tube exposed to fire. Many cracks extending longitudinally were observed on the surface of the tube as shown in Figure 1(a) and 1(b). In addition, many small blown up portions were observed on the outer surface of the tube as shown in Figure 1(c). Bulging of the tube was also observed as shown in Figure 1d. Measurement revealed that the diameter and the wall thickness of the tube at the region of failure changed from 50.8 mm to 57.8 mm and 6.35 mm to 3.5 mm, respectively. Therefore, the diameter of the tube increased and the wall thickness of the tube deceased at the region of failure. Crack section was cut in transverse direction for further analysis as shown in Figure 1(e). The presence of corrosion products at the inner surface of the tube was observed as shown in Figure 1(f).
3.2 Chemical analysis and hardness test
Chemical analysis performed on the affected and not affected regions of the tube revealed that there was no variation in composition at both the regions as shown in Table 2. The chemical analysis was further supported by hardness tests performed on these regions. Hardness measurement was carried out in
polished transverse cross sections near crack area and unaffected area as shown in Figure 1(e). The hardness value of the not affected region of the pipe was 73 HRB whereas it was 70 HRB at the failed region. Therefore, it is inferred that the tube conforms the material requirement in terms of its chemical composition and hardness.

| Sample ID                  | C    | Mn   | P    | S    | Si   | Cr   | Mo   | Ni   | V    | Al   | Cu   |
|----------------------------|------|------|------|------|------|------|------|------|------|------|------|
| Specified Composition of  | 0.15 | 0.68 | 0.015| 0.012| 0.24 | 0.023| 0.004| 0.010| 0.007| 0.033| 0.008|
| Standard Tube              |      |      |      |      |      |      |      |      |      |      |      |
| Failed Tube                | 0.154| 0.65 | 0.0084| 0.0045| 0.19 | 0.014| <0.0005| 0.0053| 0.0016| 0.034| 0.012|

3.3 Microstructural analysis
3.3.1 Analysis using optical microscopy.
In order to examine the microstructural changes in the failed tube with respect to the standard tube, optical microscopic examinations were carried out at the cross section of cracked lip portion and at a distance away from the crack region (Figure 2) on fireside area. It was observed that there are clean polygonal ferrite-pearlite grains on fireside area and was similar to those grains as they were originally specified for the material. Microstructure taken at cross sectional position of cracked lip also indicates a typical pearlite/ferrite grains. Hence, it can be stated that that the cracked area might have not undergone any microstructural changes due to localized temperature variation during its service.
3.3.2 Analysis using SEM with EDS

To analyze the type of oxide scales or deposits on the fireside as well as waterside of the failed tube, scanning electron microscopy along with EDS (Figure 3) was performed. With the help of SEM images and EDS analysis detailed mechanism of failure was determined. Through SEM images thick black oxide scales can be seen on the waterside surface and some deposits can also be found in fireside surface of the failed tube. It was confirmed by EDS analysis that thick scale on waterside surface is composed of magnetite (Fe₃O₄) while the deposits on fireside surface contain hematite and wastage (Fe₂O₃+FeO), SiO₂.
Visual analysis reveals the presence of ash deposition on the fireside surface of the failed tube. SEM-EDS analysis of the region closer to the crack lip confirms the presence of iron, oxygen, and carbon as major constituents while aluminum, silicon, sodium, sulphur and chlorine were also present in significant quantity. The existence of these elements resulted from the coal used as fuel and therefore, fly-ash and slag, which are main ingredients of combustion products, are also composed of them. Characteristics such as melting point and viscosity of slag and ash are dependent on the composition of these elements. Fly-ash particles collide with tubes by their inertial force and can adhere or deposit on tube. The presence of sodium, sulphur, iron and oxygen also suggests the possible formation of complex sulphates [5]. Deposition of Na₂SO₄ in the molten or nearly molten state would contribute to catching colliding particles. Similarly, sulfates of sodium and fly-ash deposit on to the fireside will develop the second layer further. As the second layer increases in thickness and its surface temperature rises beyond the saturation temperature of Na₂SO₄, these sulfates would stop condensing on to the wall. After that, only fly-ash would be deposited and would grow in a layer. Serious fouling will be developed if the fly-ash carried by the gas is in a molten state. There are two main mechanisms, sulfidation attack due to alkali sulfates of sodium, and corrosion caused by complex compounds of the sulfates Na₃Fe(SO₄)₃, which are formed by alkali sulfates and Fe₂O₃ contained in fly-ash. Na₂SO₄ and Fe₂O₃ deposited on to wall react with SO₃ contained in combustion gas and form complex compounds, as described by the following equation:

\[
3\text{Na}_2\text{SO}_4 + \text{Fe}_2\text{O}_3 + 3\text{SO}_3 \rightarrow 2\text{Na}_3\text{Fe} (\text{SO}_4)_3 \quad \ldots \ldots \quad (1)
\]

Thus complex compounds of Na₃Fe(SO₄)₃, [6] advance the above corrosion process cyclically. The complex compounds are not formed in the high-temperature region beyond 704 °C. That is why the corrosion rate decreases abruptly when the temperature reaches this level.

Along with this, stress also generates in the tube which in turn causes the rupture of tube. In order to evident this phenomenon hoop stress ($\sigma_h$) is calculated by using the formula $PD/2t$ where ‘$P$’ is the operational pressure, ‘$D$’ is the mean diameter of the tube and ‘$t$’ is the mean thickness of the tube at the time of failure. It was found that the calculated hoop stress is ~ 9000 psi and the recommended hoop stress for boiler tubes is 4000 psi. At the same operating pressure ‘$P$’, increase in hoop stress ($\sigma_h$) is attributed to wall thinning, due to ash corrosion, which gradually leads to increase in tube diameter (D) in the failed region. This observed over stress causes the rupture of boiler tubes.
4. Conclusions

- Ash corrosion is considered to be the main mechanisms in operation from the fireside for early failure of boiler tube. Localized water corrosion mechanism operating from the waterside of the tube is normal and slow. This type of corrosion failure occurs mainly due to the accumulation of ash deposits on the fireside as well as improper maintenance during cleaning procedures of the boiler.
- The hoop stress developed on the failed tube is almost twice than recommended stress value. Hence, the tube might have exceeded the upper limit of allowable stress in the operating temperature of 700-800 °C, resulting in rupture of the tube.

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6. References

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