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Failure investigation into the boiler tubes of power plant

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Abstract

Failure of tubes is a very critical problem in boilers. The current study describes the detailed investigation for failure of boiler tubes in the power plants. Different characterization techniques like; metallography/microscopy, hardness, chemical analysis, SEM/EDS were utilized to find out the actual cause of failure. The tubes were failed within one year of its service. It was concluded that the brittle fracture (rupture) of tubes was occurred due to over-heating caused the formation of thermally insulating thick iron oxide scale on the inner surface of the boiler tube. Evidence of hydrogen embrittlement of the boiler tube in the rupture region was also found. Insights of this investigation might be helpful for the prevention of this type of failures in future.

Keywords: Boiler tubes; Power plant; Fractography; SEM/EDS analysis; Metallography

1. Introduction

The role of boilers is to convert the water into superheated steam for power generation purposes. Generally, two major types of tube boilers are used: water-tube and fire-tube boilers. In water-tube boilers, water circulates inside the tubes and is heated externally by hot gases generated by the furnace. With fire-tube boilers, hot gas passes through one or many tubes, which through thermal conduction, heats the water surrounding them [1]. Coal is the major and cheaper source of fuel for operation of boilers. These boilers are very critical and risky equipment for electricity generation. Boiler Tubes are metal tubes placed inside of boilers. Generally, two types of failure may occur in the tubes; the material failure and operational failure. Most of the failures based on of operational maintenance problems as reported in previous studies [2]. Different damage mechanisms are responsible for such type of boiler failures. This includes failure due to corrosion, graphitization, erosion, creep, overheating and etc. [10].

The current study investigates to identify the possible cause of failure. Also provide the solution/remedies to prevent such type of repeated failures in future.

A boiler tube, made of SA-210 Grade A-1 steel (ASTM A 210) [3], ruptured within one year of its service period (as shown in Figure 1). The header tube was found to be blocked (clogged) due to scale formation (as shown in Figure 2). A study was conducted to determine the cause of rupture.

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Figure 1 Ruptured boiler tube

Figure 2 Blocked header tube

2. Method of Investigation

The following characterization techniques were utilized to investigate the actual cause of failure of tubes.

a. Visual Examination
b. Chemical Analysis
c. Hardness Test
d. Mechanical Test (Tensile)
e. Grain Size Measurement
f. Metallography/Microscopy
g. Fractography (SEM/EDS)

For analysis of scale and residue found in the clogged tube, the wet analysis technique as per ASTM D 2331 was used. The chemical analysis of the samples was performed by using Optical Emission Spectrometer (Metal Lab 75-80J, GNR, Italy) according to ASTM E 1476 [4]. Hardness of the samples was estimated by Rockwell hardness tester (Indentec, UK) according to ASTM E 18 [5]. Mechanical test (Tensile test) was performed by using Universal Tensile testing machine (WAW-1000C, Jinan Precision Testing Equipment Co. Ltd., China) according to ASTM A 370 [6]. For measurement of size of grains, samples were prepared and analyzed according to ASTM E 3 [9]. Microstructural analysis was performed via Optical Microscope (DM4000M Image Analyzer, Leica, Germany) and Scanning Electron Microscope (SEM, S-3700N, Hitachi Hi-Technologies Corporation, Japan) according to [7, 8]. Fractography was performed via Optical Microscopes (Zoom Microscope, SZX7, Olympus, Japan; DM4000M Image Analyzer, Leica, Germany) [7].

2.1. Sample Identification

The samples were extracted from the rupture zone as well as from the unaffected zone of boiler tubes for analysis (as shown in Figure 3).

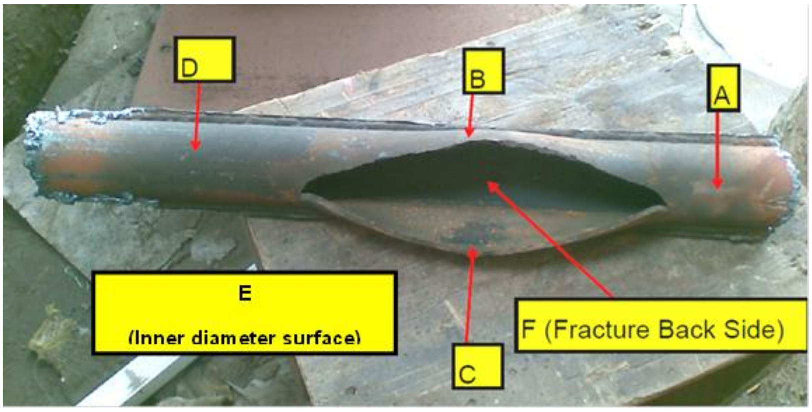

Figure 3 Locations of extracted samples of the boiler tube

2.2. Visual Examination

First of all, as received samples of tube were examined visually. A dark layer was observed on the inner surface of sample A & F, which are from the undamaged areas of the boiler tube (as shown in Figure 4). But it was not found on the inner surface of sample B & C, which are from the surrounding areas of the fractured location. However, the corrosion was observed on the inner surface of sample B & C (as shown in Figure 5).

Figure 4 Oxide layer (scale) on the inner surface of sample A & F

Figure 5 Corrosion on inner surface of sample B & C

3. Results and Discussion

3.1. Wet Analysis of Scale

The scale and residue found in the clogged tube was collected from inside of the tube. The chemical analysis of scale was performed by Wet analysis technique as per ASTM D 2331. The result shows the composition of iron oxide (as shown in Table 1).

Table 1 Wet analysis of scale and residue of clogged boiler tube.

Elements	**Composition (%)**
Iron as Fe_2O_3	87.55

3.2. Chemical Analysis

The chemical analysis of the taken samples was performed by using Optical Emission Spectrometer (Metal Lab 75-80J, GNR, Italy) according to ASTM E 1476 [4]. The results show that the chemical composition found to be within the acceptable limits.

Table 2 Chemical Composition of selected boiler tube samples.

Elements	**Composition (wt. %)**				
	Sample A (outer surface)	Sample B (outer surface)	Sample C (outer surface)	Sample E (inner surface)	Sample F (outer surface)
C	0.163	0.172	0.155	0.180	0.178
Mn	0.496	0.501	0.506	0.505	0.505
P	0.013	0.013	0.012	0.009	0.010
S	0.017	0.016	0.016	0.016	0.016
Si	0.247	0.248	0.251	0.259	0.248
Fe	Balance	Balance	Balance	Balance	Balance

3.3. Hardness Test

Hardness of the samples was estimated by Rockwell hardness tester (Indentec, UK) according to ASTM E 18 [5]. The hardness of un-damaged part (sample A & F) appears to be lower than that of fractured region (sample B, C & E). This might be due to the stresses present in the fractured region and the surrounding areas.

Table 3 Hardness test of selected boiler tube samples.

Sample	Hardness (HRB)
A	74.90
B	83
C	83.7
E	82.3
F	77.6

3.4. Tensile Test

Mechanical test (Tensile test) was performed on two samples by using Universal Tensile testing machine (WAW-1000C, Jinan Precision Testing Equipment Co. Ltd., China) according to ASTM A 370 [6]. The results are found to be within acceptable limits. However, elongation was slightly lower than the one mentioned in [1], i.e. 30%.

Table 4 Tensile test of selected boiler tube samples.

	Sample D	Sample F
Tensile Strength (MPa)	451.91	471.04
Yield Strength (MPa)	333.82	278.62
Elongation (%)	26	28

3.5. Grain Size Measurement

For measurement of size of grains, samples were prepared according to ASTM E 3 [7]. To reveal the grain boundaries, the samples were etched in 3% Nital (according to ASTM E 407 [8]. Grain size was determined according to ASTM E 112 (comparison method) [9] using Optical Microscope (DM4000M Image Analyzer, Leica, Germany). The grain size appears to be similar throughout the boiler tube with minor variations. However, around the fractured region it is observed that the grain size near the inner diameter (ID) surface is coarser than the grain size near the outer diameter (OD) surface of the boiler tube. This might be due to the formation of oxide scale on the ID surface of the boiler tube. This oxide scale acts as an insulation layer and does not allow heat trapped between the layer and the ID surface to escape. This results in over-heating, grain coarsening and softening of ID surface of the tube. However, the difference in grain size between OD & ID surface is not very significant.

Table 5 Grain size determination of selected boiler tube samples.

Sample	Average Grain Size (ASTM #)
A	7.5
B	7
C	7
E	6
F	7.5

3.6. Micro Examination

Microstructural analysis was performed via Optical Microscope (DM4000M Image Analyzer, Leica, Germany) and Scanning Electron Microscope (SEM, S-3700N, Hitachi Hi-Technologies Corporation, Japan) according to [7, 8]. The following observations were made:

The microstructure of transverse cross-sectional surfaces of samples A, B, C & F appears to be consisted of ferritic matrix with uniform distribution of pearlite (as shown in Figure 6). Whereas; the microstructure of longitudinal cross-sectional surfaces of sample A, B, C & F appears to be consisted of ferritic matrix with banded pearlite (as shown in Figure 7).

Figure 6 Transverse cross-sectional micrograph showing ferrite & pearlite.

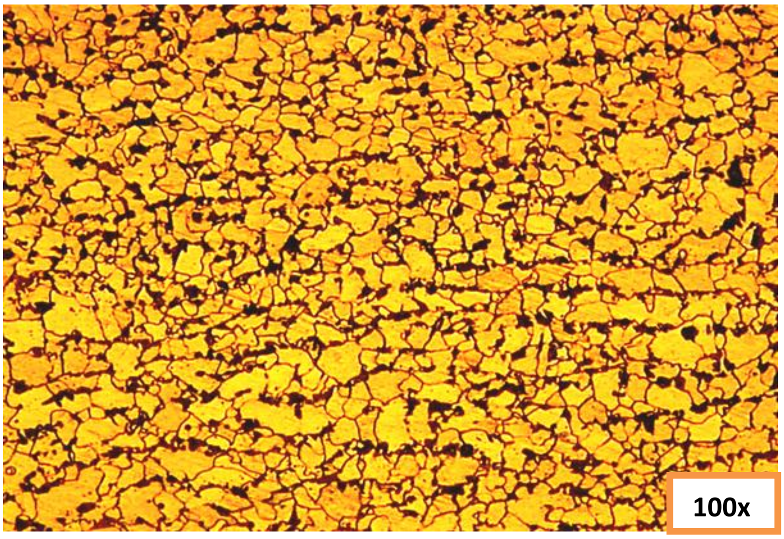

Figure 7 Longitudinal cross-sectional micrograph showing ferrite & banded pearlite

The microstructure of the inner surface near the fractured region of sample E appears to be of ferritic matrix with relatively non-uniform distribution of pearlite (as shown in Figure 8 & 9). As mentioned earlier in Section 2.7, ID surface of boiler tube experienced some grain growth due to over-heating (as shown in Figure 9). It was observed that this non-uniformity in grain size & pearlite distribution might be playing a role in the eventual failure of boiler tube.

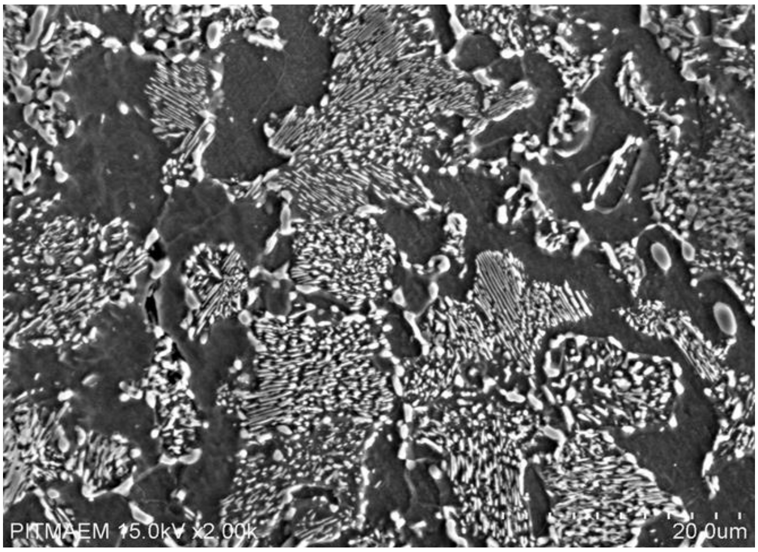

Figure 8 SEM micrograph showing ferrite and lamellar structure of pearlite

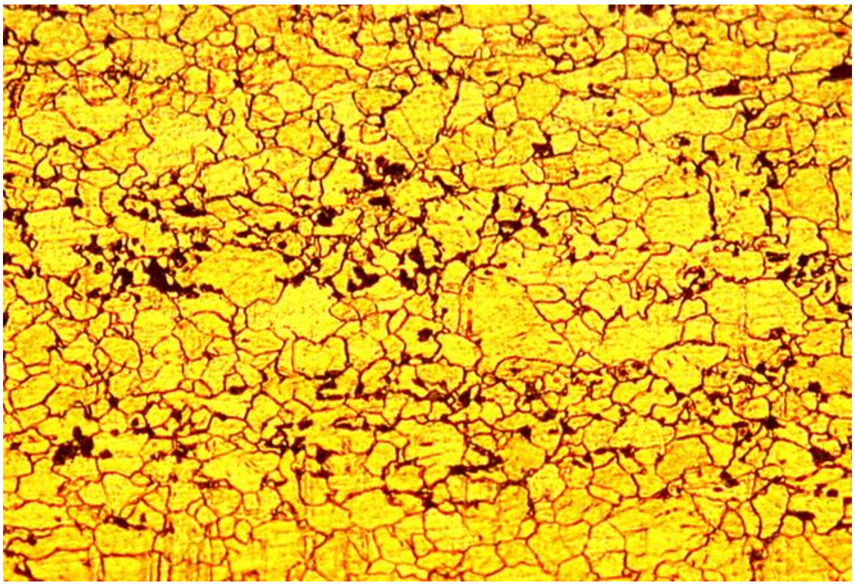

Figure 9 Cross-sectional micrograph showing grain growth and non-uniform distribution of pearlite

3.7. Fractography

Fractography was performed via Optical Microscopes (Zoom Microscope, SZX7, Olympus, Japan; DM4000M Image Analyzer, Leica, Germany), on the fractured regions of sample B. The fracture surface appears to be of brittle nature with negligible amount of plastic deformation (as shown in Figure 10). The outer diameter surface of sample B reveals cracks as indicated by arrows, which appeared to be formed during fracture (as shown in Figure 11). Transverse cross-section of fractured zone of boiler tube indicated intergranular fracture (as shown in Figure 12).

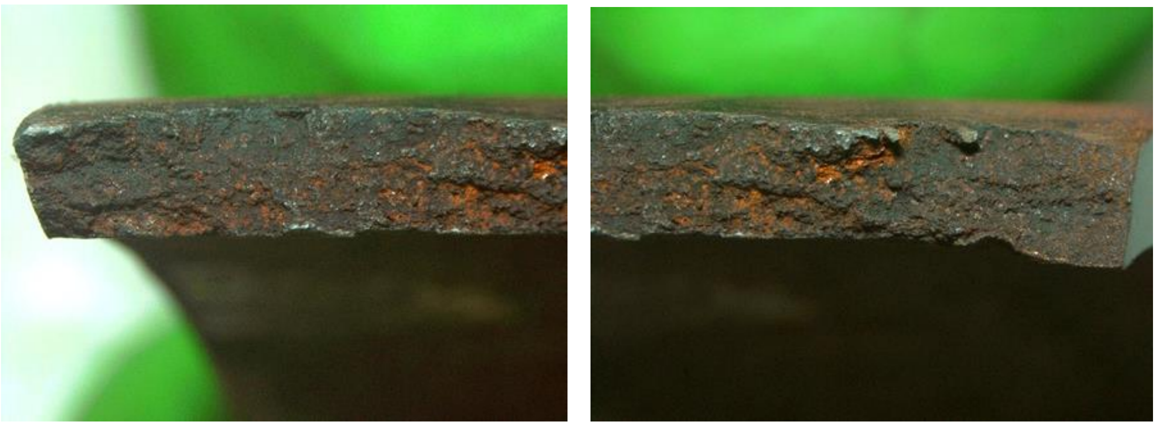

Figure 10 Fracture surface of sample B

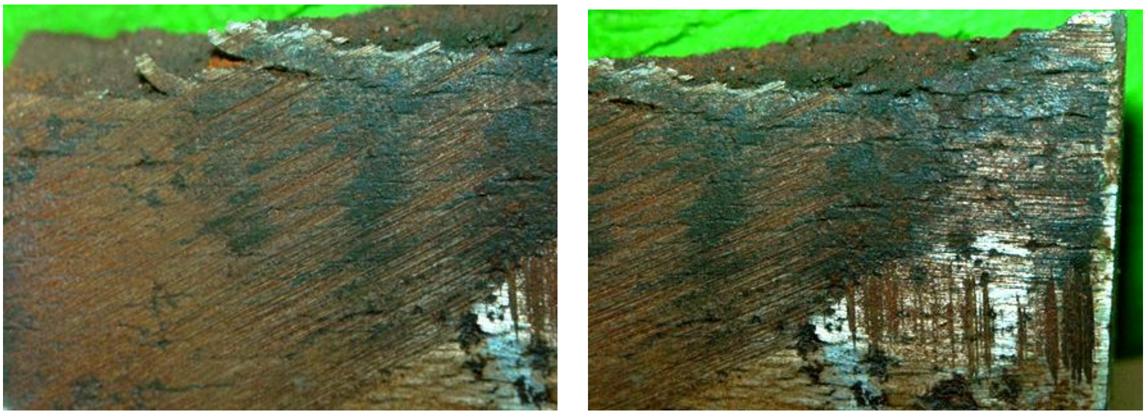

Figure 11 Top surface of sample B

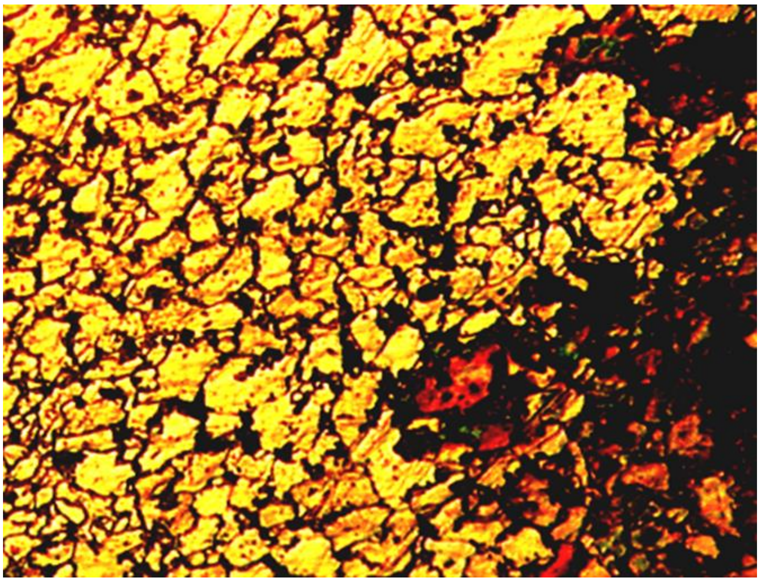

Figure 12 Transverse cross-sectional micrograph of fractured zone of boiler tube showing intergranular fracture of boiler tube (sample B)

3.8. Water analysis

The de-mineralized (DM) water used in the boiler tubes was tested for confirmation of available chemical ratios as per BS 2690. The pH value of reference DM water is reportedly 8 (as shown in Table 6).

Table 6 Analysis of de-mineralized water

Water Quality Parameters	Composition (%)
pH	7.0
Conductivity at 25°C	105.7 μs/cm
Magnesium	24.7 ppm
Magnesium as Mg^{2+}	5.9 ppm
Chloride as Cl^{1-}	9.2 ppm
Total suspended solids	None
Total dissolved solids	74.0 ppm
Sulphate as SO_4^{2-}	8.5

From the tests conducted, it appears that the unaffected/un-damaged boiler tube is free from any significant & inherent material defects. However, it was observed that grain size of inner diameter region was coarser than that of outer diameter region, which occurred during the service life of the boiler tube. As mentioned above, grain coarsening was observed in the inner diameter region of the boiler tube. This can be attributed to the formation of scale or deposits of iron oxide layer on the inner surface of the boiler tube. These deposits or internal scale have a lower thermal conductivity than the steel tube. The net effect is an increase in tube metal temperatures, which appeared to have led to grain growth and subsequently to premature creep failure. This is also supported by the blockage of the header tube. Hydrogen also appears to be one of the factors that contributed to the boiler tube failure. Presence of chlorides (like magnesium chloride) in boiler tube water assists hydrogen embrittlement by lowering the pH value. This leads to evolution of hydrogen. This hydrogen enters the tube in the form of methane gas and eventually settles along the grain boundaries of the tube. This results in hydrogen embrittlement. The hardness of the fractured region was higher than that of un-damaged region. This appears to be due to stresses generated because of hydrogen embrittlement. Other indicators of failure caused by hydrogen embrittlement include brittle nature of the failure, intergranular fracture and the internal oxide scales. The hard, adherent, nonporous tube deposits (oxide scales) combined with the lowering of pH value of boiler tube water also assist in hydrogen embrittlement.

4. Conclusion

On the basis of above mentioned results and discussion, it was concluded that, the brittle fracture (rupture) of tubes was occurred due to over-heating caused the formation of thermally insulating thick iron oxide scale on the inner surface of the boiler tube. This may be prevented by proper maintenance of tubes.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare no conflict of interest for the current paper.

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