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Failure analysis of high strength T91 boiler tubes used in thermal power plant: A case study

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A power generating utility of 600 MW has reported the failure of boiler tubes after a service life of 265 hours against the design life of 25-30 years. The failure of tubes was reported in Re-heater Inlet Coil tubes which were made up of high strength material alloy of SA 213 T91 grade. These boiler tubes were operating under a high temperature and pressure. The material used for re-heater and super-heater boiler tubes should have enough creep strength to sustain at high temperature and pressure. Even though T91 grade steel has superior quality of metallurgical properties in comparison to low alloy existing material like T11, T12 and T22, T91tube was failed in a short duration. This paper describesthe investigation of the failure of high strength T91 gradereheater tubes in a coal fired thermal power plant. The failure investigation covers visual inspection, dimensional measurement, hardness mapping, oxide scale measurement, microstructural studies, and SEM and EDX analysis of the failed tubes. The analysis reveals that Tube No-3 of re-heater boiler tube failed due to short term overheating and other tubes failed due to secondary damage caused by steam impingement.

***Keywords** : Re-heater boiler tube, visual inspection, grade identification of alloy, dimensional and hardness measurement, oxide scale measurement, microstructure analysis.*

1.0 INTRODUCTION

Boilers are used for generating super-heated steam at high pressure and temperature and subsequently this superheated steam is used to run the turbine for generating electricity. Boiler components which are working at high temperature and pressure undergo continuous degradation which further results in failure. Since boiler being the heart for the steam generating system, failure of its components will lead in forced outages of the plant, resulting in heavy economic losses in terms of non–availability of plant. Periodic inspection of boiler tubes has a great impact on the generation of power and economic status. The periodic assessment of the component of boiler particularly its tubes minimized the risk of forced outage of the thermal power plant.

Materials with good creep strength and high temperature oxidation stability are required in a thermal power plant. Alloy steel containing chromium –molybdenum possess good strength and better oxidation stability [1-4]. The material grade of T91 possesses high temperature strength and oxidation resistance than those widely used material such as T11 and T22 grade [4-8].

Repeated failures were reported through boiler operating persons in re-heater section tubes of (high strength material grade of SA213 T91) 600 MW boiler. The boiler operating persons have collected four failed tubes from same coil with suspecting one of the tube with primary failure and other three tubes as secondary failure. All the failed tubes were thoroughly visually examined and different laboratory analysis such as

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dimensional measurement, chemical composition analysis, hardness measurement and oxide scale measurement was carried out. Microstructure and SEM and EDX analysis were also done to identify the cause of repetitive failures. Microstructure analysis revealed that the increasing percentage of austenite indicates that the tube has experienced overheating for a short period of time. This paper presents the failure analysis of boiler tubes of re-heater zone of a fossil fired thermal power plant.

2.0 EXPERIMENTAL PROCEDURE

Four failed re-heater inlet coil tubes (from same coil) [Sample 1: Tube No.-1, Sample 2: Tube No.-2, Sample 3: Tube No-3 and Sample 4: Tube No - 6] (details are shown in Figure 1) was received through operating persons from operation sites of the thermal power plant. The tubes were cleaned carefully to remove dirt and other external impurities for visual observation and metallographic sample preparation. Samples were taken near failed region from each tube to identify the mode of failure. The samples were polished by conventional metallographic techniques with silicon carbide grit paper and further cloth polishing. The polished samples were etched with 2% nital for T22, carpenters ss etch for SS 347 and adler etchant solution for T91 grade steels for analysis of microstructure under optical microscope. Chemical composition and SEM and EDX analysis and hardness testing were carried out on the samples at different locations

3.0 RESULTS

3.1 Visual Observation

Visual observation of the tube samples showed large opening (fish mouth opening, bull eye type opening, window opening) near the bend section in every tube. The photograph of the failed tubes indicating the nature of crack opening is shown in Figure 1.

- Tube No. - 1: An opening is observed near the bend section of the tube. The opening is at the opposite direction of the flue gas flow. Near the opening, steam erosion is also observed on the tube surface. Neither swelling nor any scale/deposit was observed inside the tube. No other marks other than steam erosion patches were observed. Localized thinning is observed i.e. at the area of steam erosion section.
- Tube No. -2: A complete opening was observed near the bend section of the tube and bull eye type opening in other region. The failure section is in the 5 to 10 O' Clock position (flue gas direction is considered as 12 O' clock position). Steam erosion is observed in the failed region. Neither swelling nor any scale/deposit was observed inside the tube. Thinning observed only in the steam eroded section.
- Tube No. -3: In this tube fish mouth opening and window type opening is observed. The window type opening is observed along 7 to 9 O 'Clock position which is observed due to steam erosion caused by other adjacent tube leakage. The fish mouth opening is observed near the bend section along the 8 to 10 O' clock position. Excessive amount of bulging is observed around this area. Stretch marks are observed near the failed section both from outside as well as from inside of the tube. The fracture surface shows thin lip knife edge. Neither scaling nor deposits were observed from inside of the failed tube.
- Tube No. -6: A bull eye type and complete opening is observed on the tube surface. The failed section is observed along 6 to 11 O' Clock position. Steam erosion patches are observed along the failed section. Neither swelling nor any scale/deposit was observed inside the tube. Thinning is observed only in the steam eroded section.

3.2 Dimension Measurement

The tube metal wall thicknesses at different regions were measured near the damaged section and around un-damaged (away from damaged location) section using digital venire (Make-Mitutoyo™) and DM4DL (Make- Krautkramer™). The measured thickness reading are given Table 1.

3.3 Chemical Composition Analysis

The grades of the re-heater tubes were identified by using Innov X System (™) which works on the principle of XRF technique and the results are given in Table 2. The grades of boiler tubes confirm as per the design criteria.

3.4 Hardness Measurement

The hardness value of tube sample was measured at different locations using Equotip 3 (Make- Proceq ™) portable hardness tester in Brinell hardness scale and the results are given in Table 3.

3.5 Oxide Scale Thickness Measurement

The inside oxide scale thickness were measured at different locations on the failed boiler tubes using OLYMPUS (™) 38DL plus with a probe of 20 MHz. No oxide scale (< 180 micron, minimum detection level of the equipment is 180 micron) were detected in Sample Tube No-1, 2& 6 where as in Sample Tube No-3 minor oxide scaling (180 to 210 micron) were observed.

3.6 Microstructural Analysis

For the metallurgical analysis sampling were done from different location of the failed tubes. These samples were mounted in Bakelite and its surface were grinded with belt grinder followed by polishing with emery paper(Silicon carbide grit) of 220, 320, 500, 800, 1000 and then followed by 3 µm and 1 µm with diamond suspension on cloth polish (disc polisher of variable speed) to give the mirror finish touch. When the samples were mirror polished it were etched with freshly prepared suitable etchants for few seconds to reveal the microstructure. After proper etching, the samples were observed under high power metallurgical microscope, Axio-Imager M1m (Make- Zeiss TM) and the microstructure are given in Figure 2 and 3.

Since there are no changes in the microstructure for the samples taken from tubes 1, 2 & 6, it indicates that these tubes have failed due to steam impingement. The failures modes of the tubes 1, 2 and 6 are secondary damaged.

Samples were also taken from the different section of primary failed tube (Tube No-3) i.e from the tip of fish mouth opening and away from the failed section for the microstructural analysis as shown in Figure 4. The microstructures of sample taken from the tip of fish mouth opening region showed relatively more carbide precipitation compared to sampling taken away from the fish mouth opening.

4.0 SEM (SCANNING ELECTRON MICROSCOPE) AND EDX (ENERGY DISPERSIVE X-RAY) ANALYSIS

For SEM analysis sampling were done from the tip of fish mouth opening and stretch marked region from primary failed tube i.e. Tube No-3. The samples were ultrasonic cleaned and observed under Scanning Electron Microscope (SEM) and the results are given in Figure 5 and 6 respectively.

The SEM photograph in Figure 5 shows the many crack lines and the fly ash particles on the tube metal surface and in between the stretched lines. The SEM photograph shows the material has got little ductile failure before opening indicating the high temperature effect for short time of period. The same sample was analysed through EDX and the results are shown in Figure 6. The spectrum taken from the metal surface shows more percentage of iron oxide (more than 70%) and less alumina and silica while the spectrum taken from the slag region shows more percentage of alumina and silica (around 95%) and no iron oxide in the case of flue dust particle.

TABLE 1

Particular	Measured Dimension (mm)			Remarks
	Thickness (away from erosion/ failed section)	Thickness (near the erosion/ failed section)	OD	
Tube No- 1	3.80 to 4.26	1.98 to 2.30	62.92	Thinning (up to 50%) in steam erosion section observed.
Tube No- 2	3.87 to 4.54	2.15 to 2.93	64.02	Thinning (up to 45%) in steam erosion section observed
Tube No- 3	3.8 to 4.02 (opposite of ruptured section)	2.06 to 2.93 (near the ruptured section)	68.71& [89 to 103 near ruptured section]	Thinning (up to 46%) along the longitudinal direction of the ruptured section, bulging on OD (up to 60%) also observed.
Tube No- 6	3.98 to 4.4	2.78 to 3.04	63.77	Thinning (up to 38%) in steam erosion section observed

TABLE 2

SI No.	Tube Description	Element Wt (in %)					Grade of Tube
		Cr	Mn	Ni	Nb	Mo	
1	Tube No- 1	17.83	1.28	8.81	0.52	0.20	SS347
2	Tube No- 2	8.51	0.53	-	-	0.93	T91
3	Tube No- 3	8.50	0.52	-	-	0.96	T91
4	Tube No- 6	2.17	0.43	-	-	0.95	T22

TABLE 3

Particular	Hardness (BHN)		
	Away from erosion/ failed section	Near the erosion/ failed section	At 180^0 from the erosion/ failed section
Tube No- 1	135 to 150	107 to 160	160 to 170
Tube No- 2	160 to 174	147 to 160	152 to 162
Tube No- 3	109 to 127	92 to 97	110 to 125
Tube No- 6	124 to 139	107 to 130	122 to 130

	
Opening near the bend section	Bull eye type & complete opening
	
Fish mouth & window type opening	Bull eye type &complete opening

FIG. 1 FAILED BOILER TUBES (AS RECEIVED)

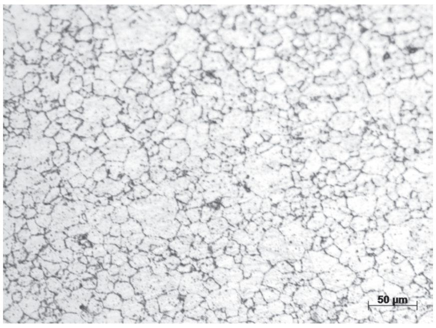
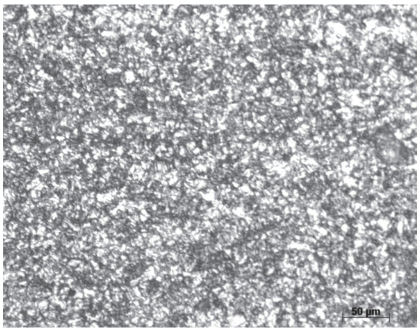
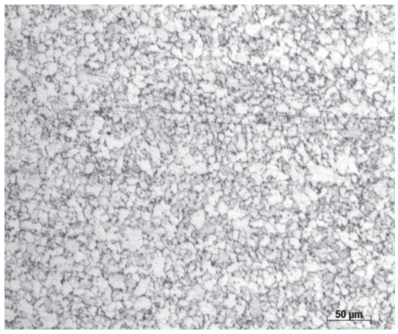
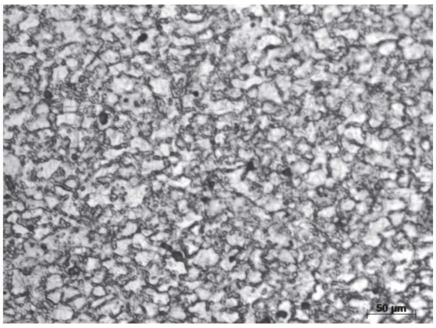
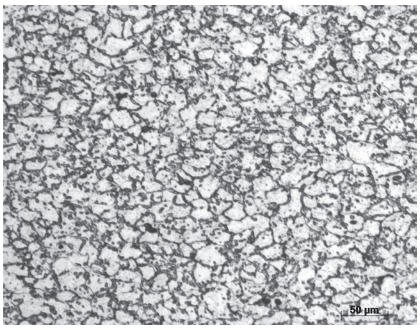
		
Tube No- 1, 200X Sample taken from erosion failed section: The structure shows normal austenitic phase.	Tube No- 2, 200X Sample taken from erosion failed section: The structure shows normal ferrite tempered martensite.	Tube No- 6, 200X Sample taken from erosion failed section: The structure shows normal ferrite and pearlite

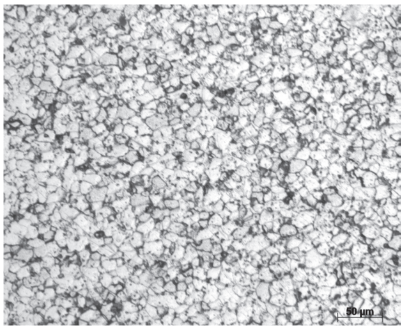
FIG. 2 MICROSTRUCTURE OF THE SAMPLES TAKEN FROM FAILED TUBES 1, 2 & 6



Sample taken away from the fish mouth opening section: The structure shows minor in-situ precipitation of carbide along grain boundary.



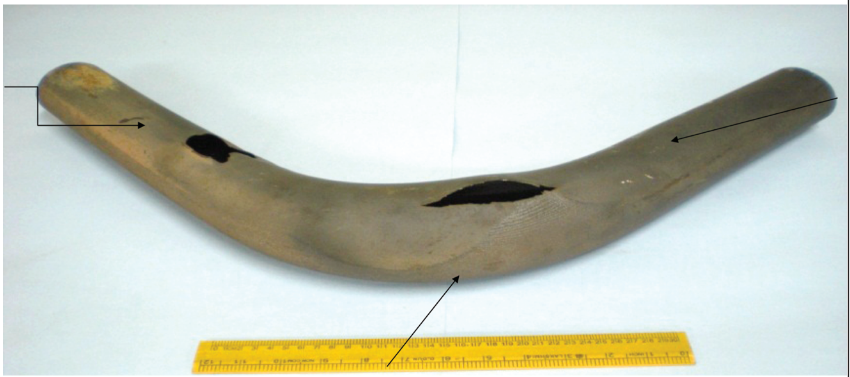
Sample taken from another location of fish mouth opening section: The structure shows precipitated carbide along grain boundary.



Sample taken from tip of the fish mouth opening section: The structure shows precipitation of carbide along grain boundary and creep void formation

FIG. 3 MICROSTRUCTURE OF SAMPLES TAKEN FROM FAILED TUBE NO 3 (200X)

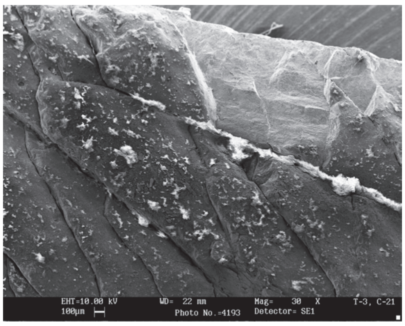
Sampling away from failed region

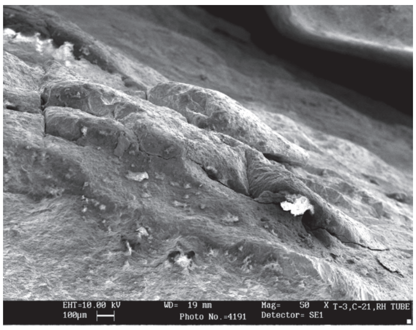


sampling from tip section of fish mouth opening

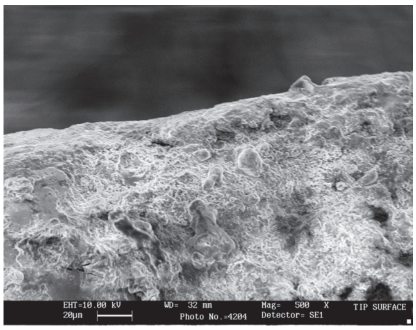
Sampling from another position of fish mouth opening

FIG. 4 POSITIONS OF SAMPLING FROMPRIMARY FAILED TUBE (TUBE NO-3)



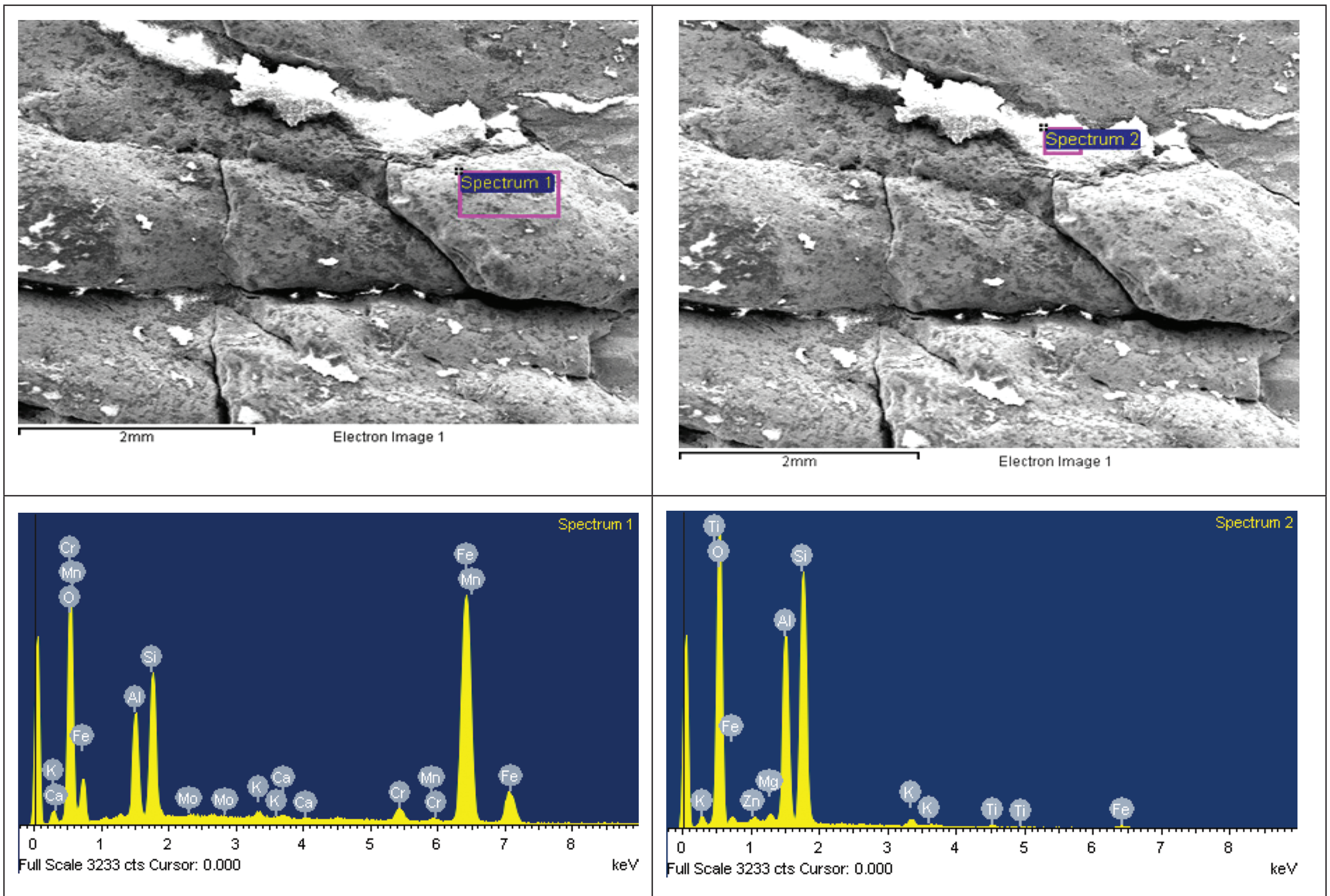


Sample taken from stretch marked region showing crack lines with fly ash particles.



Sample taken from tip of fish mouth opening showing less ductility

FIG. 5 SEM PHOTOGRAPH



Constituents from metal surface (Wt.%): Al_2O_3-9.95, SiO_2-14.59, K_2O-0.41, Fe_2O_3-71.55, TiO_2- 0.41 & Cr_2O_3-2.69	Constituents from slag region (Wt.%): Al_2O_3-32.35, SiO_2-62.53, K_2O-1.44, Fe_2O_3-1.47, TiO_2- 0.89 &MgO- 1.32

FIG. 6 EDX RESULTS

5.0 DISCUSSIONS

The visual observations for all the four samples revealed large opening. Longitudinal wall thinning was observed in the Sample Tube No-3 along the fish mouth opening. Stretch marks (thermally deteriorated) are also observed around the region of fish mouth opening. The fracture surface of the fish mouth opening shows thin lip with knife edged. The surface shows little ductility in nature that may be due to short time exposure of high temperature effect and the surface got oxidized. There are no abrupt changes in the microstructure of the tubes sample taken from sample tube no- 1, 2 and 6 i.e. secondary damaged tubes. While the microstructure of the tubes samples taken from different region from fish mouth opening Sample tube no-3 shows more amount of austenite phase and precipitated carbide in-comparison to sample taken from away of the fish mouth opening. The increasing percentage of carbides indicates that the tube has experienced overheating for a short period of time. The SEM results of the fracture surface shows many cracks line in the region of stretch marks, the fractrograph surface show little ductility in nature. The less ductility observed on the fracture surface indicates for overheating for shorter time of period.

6.0 CONCLUSIONS

The boiler Tube No. 1, Tube No. 2 and Tube No. 6 are secondary failure due to steam erosion/ impingement.

In tube No. 3, neither any deposit nor any oxide scale was observed inside the tube. The bulging with stretch mark was observed in the localised area of fish mouth opening region. The microstructure of the sample taken from the tip of fish mouth opening shows more percentage of carbide precipitation. The increasing percentage of carbide precipitation in the localised region indicates for overheating for a short duration of time. From the analysis it is concluded that the tube has failed due to short term overheating [1, 3, 7]. The short term overheating may be due to any one or combination of the factors like, loss of enough coolant circulation, uneven firing of fuel burner, and large fluctuation in load swing or change in firing pattern.

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