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Failure Analysis and Integrity Assessment of Aging Boiler Bank Tubes of HRSG

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ABSTRACT

In oil and gas processing plants, heat recovery steam generators (HRSG) continue to make great strides in efficiency and reliability for power generation. But tube failures continue to cause forced outages. To operate at peak capacity, it is necessary for a plant to find ways to avoid tube failures, as well as to quickly recover when forced outages take place. Finding the root cause for a failure is a very important step in preventing future failures.

A cogeneration plant installed in one of the gas processing plant was operating HRSG boilers that were in continuous operation for more than 20 years. In one of the boilers, boiler bank tubes failures had been reported a couple of times in a month. Lifetime of tubing was not mentioned by the manufacturer in the manual. Failed tubes were subjected to various laboratory investigations to understand the cause of failure.

Corrosion product analysis showed the presence of several ions like Fe, O, Ca, P, Si, Al, Mg, which were deposited on the internal surface of the tube. These deposits acted as an insulator and excessive deposits prevented efficient heat transfer through the tubes to the water. This caused the metal to become overheated. Long term heating caused distinctive microstructural change in both external and internal surface of the tubing due to decarburisation initially around pearlite then gradually spreading leading to intergranular metal loss. From laboratory investigations, it was found that the cause of the metal loss and eventual failure was flow accelerated corrosion (FAC) and erosion. FAC in consonance with microstructural changes resulted in the direct removal of iron from the internal surface of the

tube and made it abrasive, thus accelerating the rate of metal loss from the tube surface by erosion.

A study was carried out on cut samples of otherwise healthy bank tubes of another HRSG to ascertain its health and make a comparison of the tube conditions of both HRSGs. The tube samples were subjected to similar analyses to understand the health, material integrity, morphology of the tube surface. From the laboratory investigations it was found that the tube surface of this HRSG exhibited morphology similar to the failed tubing. The tubes of this HRSG are susceptible to failure under FAC and erosion in a manner similar to the failed tubing, as inter-granular metal loss and similar microstructural change were observed in both tubing.

INTRODUCTION

In oil and gas processing plants, heat recovery steam generators (HRSG) continues to make great strides in efficiency and reliability for power generation. But tube failures continue to cause forced outages.

A cogeneration plant installed in one of the gas processing plant was operating two HRSG (I & II) boilers that were in continuous operation for more than 20 years. The boilers HRSG- I & II are of same make, design and commissioned during the same time. They have worked under the same operating conditions over the last 21 years.. To date, no tube failure has been encountered in HRSG- I (Fig 1) . In HRSG II, boiler bank tubes failures had been reported a couple of times in a span of one month (Fig 2). Lifetime of tubing was not mentioned by the manufactuer in the manual. Failed tubes were subjected to various laboratory investigations with respect to their chemical composition, metallurgy, hardness, and fractography to understand the cause of the failure. As per the OEM these types of failures are common after 20 years of continuous operation. In view of the above observation, similar tests were carried out on the cut samples of otherwise healthy boiler bank tubes of HRSG- I to ascertain its health and make a comparison of the tube conditions of both the HRSGs.

Figure 1: Boiler bank tubes og HRSG I

Figure 2: Failed tubes of HRSG-II

Details of the boiler bank tubes :

Material of construction	ASTM A 192.
Date of Commissioning	December 1988
Date of first failure of HRSG II	23.04.2009
Design pressure, Kg/cm^2 ,	15
Operating pressure, Kg/cm^2	7.5
Design temperature-^oC	200
Operating temperature -^oC	170
Configuration of the line at the location of leaks	At bend portions towards upper drum.
Position of the leakage:	12 O'clock
Design life:	Lifetime of tubing was not mentioned by the manufactuer in the manual
Internal Environment:	Pressurised hot water/ steam
External Environment	Flue gases
Any protection measures taken during shutdowns to avoid ingress of oxygen.	The boiler was in continuous operation. Shut down was taken during annual maintenance for about 15 days. No protection measures were taken during this period to avoid ingress of oxygen.
Deatil of corrosion protection measures	Na_3PO_4 and N_2H_4 were injected daily basis.

EXPERIMENTAL PROCEDURES:

VISUAL INSPECTION:

HRSG II-

- The OD of the failed tube was 51.2 mm and the ID was 43.2 mm.
- There was no external corrosion.
- The tubing had ruptured at the outer periphery of the elbow of the tubes.
- There was a big hole of 60mm length and 20 mm breadth. Metal near the hole had thinned down to the extent of 0.88 mm (Figure 2).
- Internal surface of the tube did not have metal thinning except near the hole. Internal corrosion typical of flow assisted corrosion was observed at the 12 O'clock side of the bend.

HRSG I

- The OD of the tube was 51.2 mm and the ID was 43.2 mm.
- There was no external corrosion.
- Internal surface of the tube did not have metal thinning.

WALL THICKNESS GAUGING:

Wall thickness gauging of the tube samples were carried out by ultrasonic thickness gauge both at the plant as well as in the laboratory.

ELEMENTAL COMPOSITION ANALYSIS:

Chemical compositional analyses of the tubes were carried out by spark spectrometric analysis as per test method ASTM – E415-99A (2005).

TENSILE STRENGTH TEST

Tensile strength testing was carried out at room temperature on a longitudinal sample piece of the tubing as per ASTM A370 specifications. Tensile test included determination of yield strength, ultimate tensile strength, and elongation.

CORROSION PRODUCT ANALYSIS BY EDS:

The corrosion product was collected from the internal surface of the tubes and analyzed using SEM-EDS.

STEREOMICROSCOPY:

The internal surfaces of the elbow of the HRSG tubes were viewed under a stereomicroscope.

METALLURGICAL STUDIES:

Sections were cut from the tube samples for detailed microstructural analysis. Metallographic sample preparation was done by grinding the samples with emery papers of different grits (through 120 to 800 grit sizes). Thereafter these samples were polished with diamond paste on a polisher to achieve a finish of 1.0μ. The prepared surface was cleaned properly and dried. These specimens were observed under an inverted metallurgical microscope (Nikon - EPIPHOT TME) for inclusions/stringers etc. No significant inclusions were observed. All the specimens were etched with 2% Nital and observed under an inverted metallurgical microscope at different magnifications to study the microstructure.

HARDNESS TESTING:

Hardness of the tubing samples were measured on a representative hardness test specimen in the laboratory using a Vickers Hardness tester. Indentations were made with 3.0 kg load and observed at 400X magnification. Indentations were made across the thickness of the tubing.

SCANNING ELECTRON MICROSCOPIC STUDY:

The internal surface of both the HRSG-I and II tube samples were ultrasonically cleaned and were examined under Scanning Electron Microscope.

EXPERIMENTAL RESULTS:

WALL THICKNESS GAUGING

Table 1: Thickness data of the tubes of HRSG II measured at the plant site.

1st row Tube no.	Thickness(mm)	2nd row Tube no.	Thickness(mm)
1.	1.9	39	2.5
2.	1.6	41	2.2
3.	1.8	46	2.6
4	1.9	50	2.5
5-24 plugged		55	2.0
25	2.4	59	-
29	2.2	60	2.1
33	2.2		
35	1.9		
39	2.2		
41	2.4		
46	2.1		
50	2.3		
55	2.3		
59	2.0		
60	2.1		
62	2.1		

Table 2: Thickness data of the boiler tube samples measured at laboratory.

Position on the tube sample	Measured thickness (mm) **HRSG I**	Average Thickness (mm) **HRSG I**	Measured thickness (mm) **HRSG II**	Average Thickness (mm) **HRSG II**
12 O'clock (Extrados of elbow) position	3.3,3.3,3.3	3.3	2.1,2.5, 2.3	2.3
3 O' clock position	3.5,3.5,3.5	3.5	3.4,3.5, 3.4	3.4
6 O' clock (intrados of elbow position	3.6,3.7,3.6	3.6	3.4,3.6, 3.8	3.6
9 O' clock position	3.3,3.5,3.5	3.5	3.3,3.4, 3.5	3.4

No significant thickness reduction was observed in the tube samples except at the 12 O'clock positions (Extrados of elbow) of both HRSG-I and II. In the 12 O'clock positions in the failed sample of HRSG-II it measured 2.3 mm whereas it measured 3.3 mm for the sample of HRSG-I.

ELEMENTAL COMPOSITION ANALYSIS:

Table 3: Chemical composition analysis of the tube metal.

% Composition Element	Tube HRSG I	Tube HRSG II	Std ASTM A-192
Carbon	0.086	0.14	0.06-0.18
Silicon	0.23	0.25	0.25 (max)
Manganese	0.50	0.51	0.27-0.63
Phosphorus	0.015	0.020	0.035 (max)
Sulfur	0.008	0.012	0.035 (max)
Nickel	0.016	0.051	-
Chrome	0.019	0.074	-
Molybdenum	0.001	0.023	-
Copper	0.019	0.019	-
Iron	Balance	Balance	Balance

The chemical compositional analysis showed that the tube material of both HRSG I and HRSG II conform to ASTM A-192 specifications

TENSILE STRENGTH TEST

Table 4: Tensile Strength Test Results for Tube samples

Sl. No.	Parameter	Parent Metal HRSG I	Parent Metal HRSG II	Std ASTM A-192
1	Yield strength N/mm^2	238	289	180 (min)
2	Tensile strength N/mm^2	406	403	325 (min)
3	% Elongation	22.6	27.52	35

Tensile strength, yield strength properties of both HRSG I and HRSG II tube sample conformed to ASTM A-192 specifications. However, the percentage elongation of both HRSG I and HRSG II tube samples were not in conformance to ASTM A-192 which may be due to prolonged exposure of the tube to high temperature.

CORROSION PRODUCT ANALYSIS BY EDS

Table- 5: EDS analysis of corrosion products in the internal tube surface

Elements	Weight% HRSG-I	Weight% HRSG-II
O	20.95	23.96
Al	0.39	0.51
P	2.49	1.37
Ti	0.43	ND*
Fe	64.63	65.24
Mg	1.29	1.69
Si	1.16	3.28
Ca	5.65	2.87
Mn	2.23	1.09
Zn	0.78	ND*

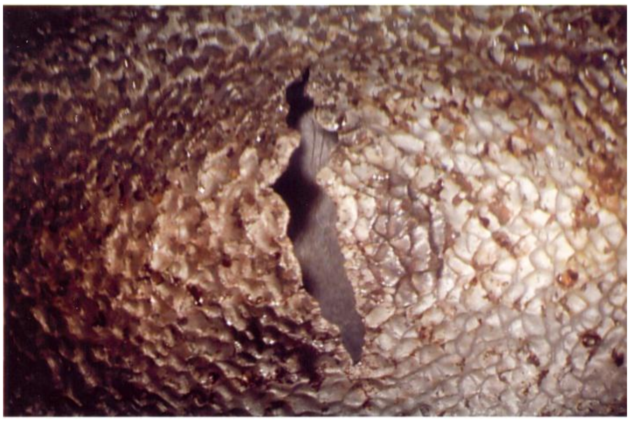
ND*- Not Detected.

Corrosion product analysis showed the presence of several ions like Fe, O, Ca, P, Si, Al, Mg, which were deposited on the internal surface of the tube. These deposits acted as an insulator and excessive deposits prevented efficient heat transfer through the tubes to the water

STEREOMICROSCOPY:

Under the stereomicroscope, directional pattern of attack from Left to right typical of flow assisted corrosion were observed at the outer surface of the bend. Such marks were absent at the other parts of the bend.

Figure 3: Internal attack in the HRSG-I showing the directional pattern typical of Flow Accelerated Corrosion (FAC)



Features typifying the flow accelerated corrosion were more pronounced in the failed tube sample of HRSG-II. Scallops and directional pattern of internal attack at the outer surface of the elbow typical of FAC were clearly visible.

Figure 4: Internal attack in the HRSG-II showing the directional pattern typical of Flow Accelerated Corrosion (FAC)

The microstructure of the parent metal revealed uniformly distributed pearlite in the matrix of ferrite.

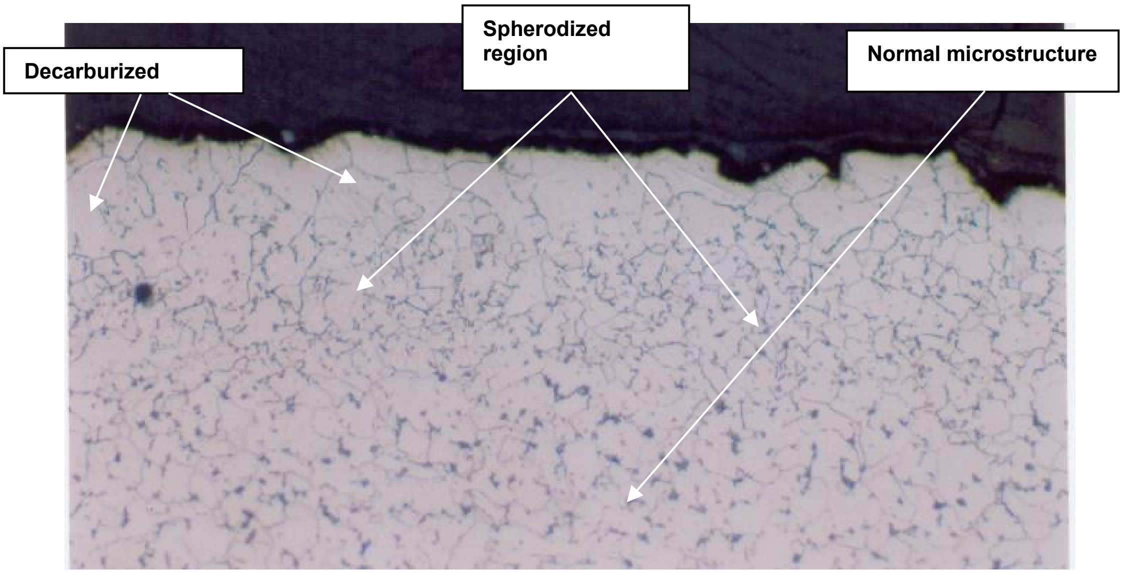
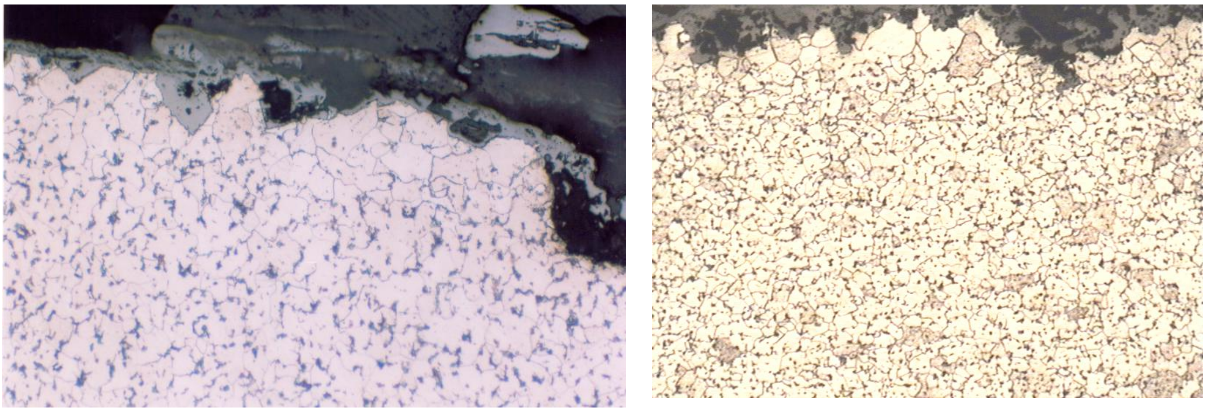


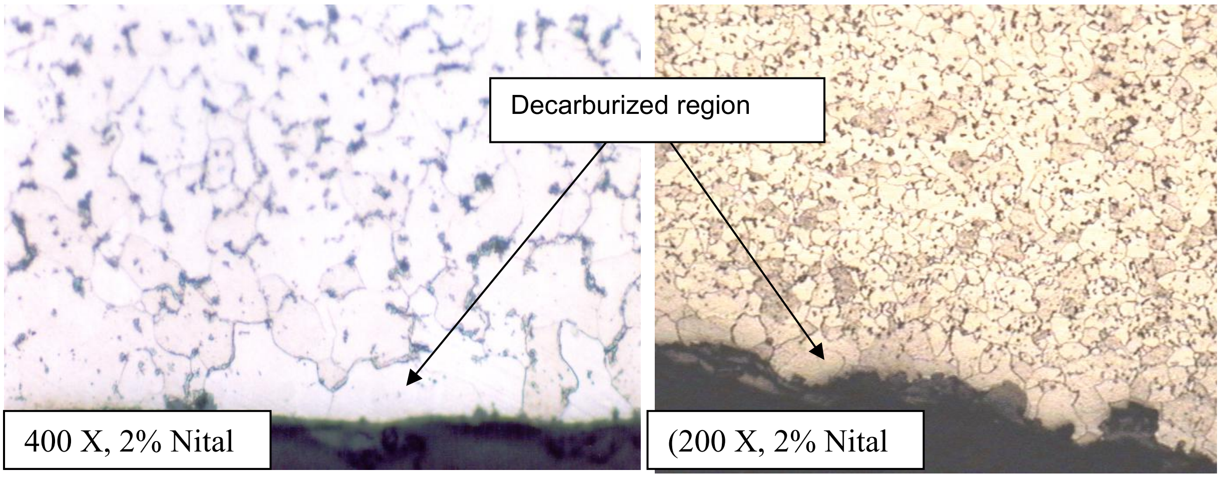
Figure 5

When carbon steels are exposed to temperatures above 482°C but less than the lower critical temperature (723°C) this steel is subjected to spheroidization. The carbides present in the steel in the annealed condition were not in their lower energy state and exposure to higher temperature resulted in the coalescence of these carbides into spheroidal form.

Due to prolong heating of tubes at the sub critical temperature range, spherodization of the pearlite had taken place. Lamellae of cementite in the pearlite had broken at the ferrite grain boundaries. Both the internal as well as the external surface of the tube had undergone decarburization as well as metal loss in intergranular manner (Figure 5). The microstructural features observed on the tube sample of HRSG-I (Figure 6) was identical to those observed on the failed sample of HRSG-II (Figure 7).



Figures 6 and 7: Internal surface of the tube of HRSG I&II showing ferrite pearlite microstructure and intergranular metal loss. (Mag.-200 X ,Etchant-2% Nital)



Figures 8 and 9: External surface of the tube showing distinct band of decarburized microstructure and intergrannular metal loss in the decarburized zone.

The metallographic studies confirmed the ferrite pearlite microstructure of a carbon steel material. It also suggested that the material had undergone spherodization and decarburization due to prolonged heating in the subcritical temperature range and metal loss had occurred both on the external and internal surface of the tubing in an intergranular manner (Fig 8&9). The features observed on the tube sample of HRSG-I (Figure 8) were identical to those observed on the failed sample of HRSG-II (Figure 9).

HARDNESS TESTING:

The hardness measurements were made and the average hardness of the tube sample was found to be 138 HV3. The measured average hardness of the failed tube sample of HRSG-

II was 141 Hv3. Hardness measurement of tube samples of both HRSG-I & II were within the specified limit for ASTM-A -192 grade materials.

SCANNING ELECTRON MICROSCOPIC STUDY:

At the outer bend of the tube sample, morphology typical of FAC attack was observed in both HRSG I (Figure 10) and HRSG II (Figure 11) samples.

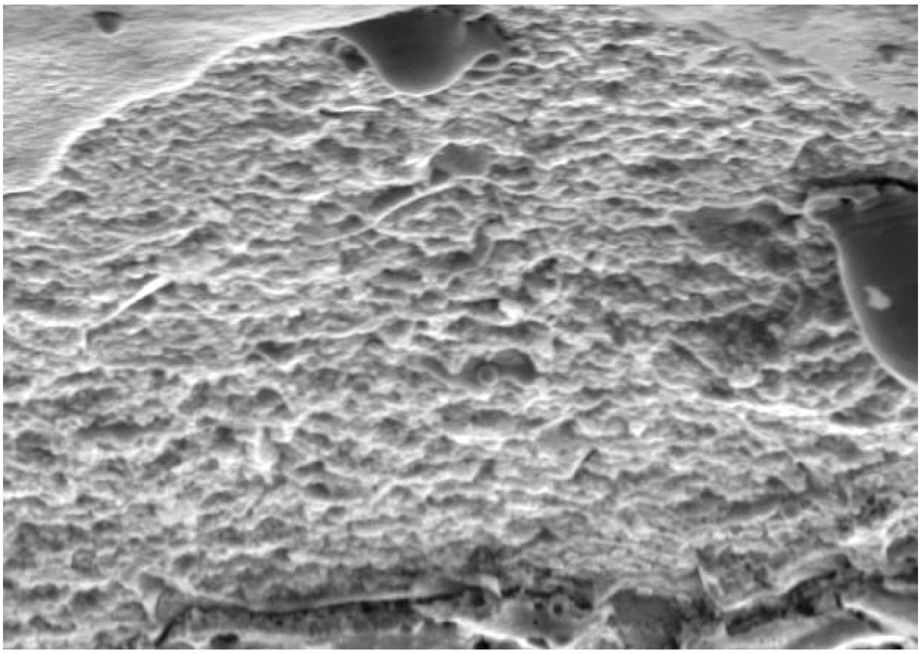


Figure 10: Scallops typical of FAC as observed at the outer bend of HRSG-I.

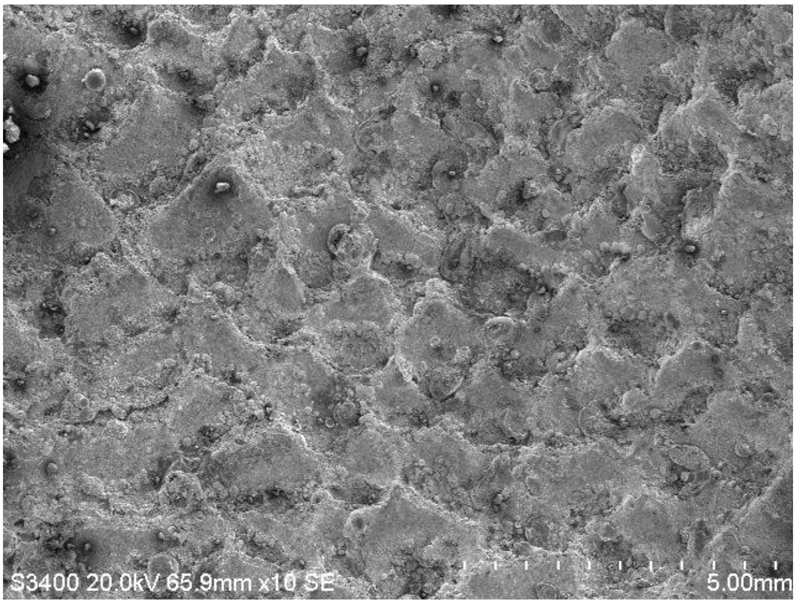
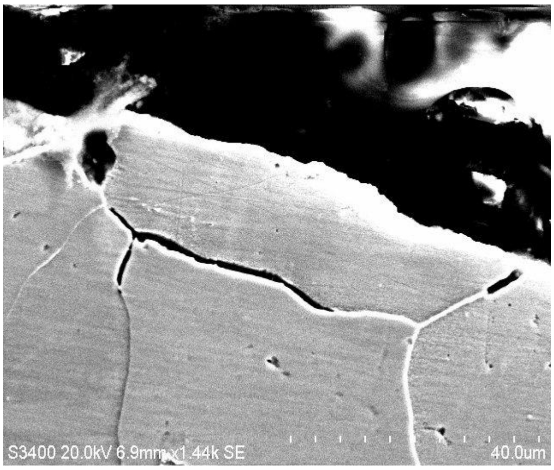
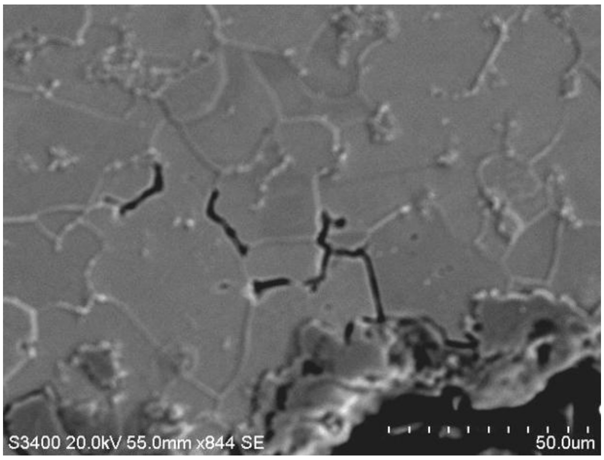


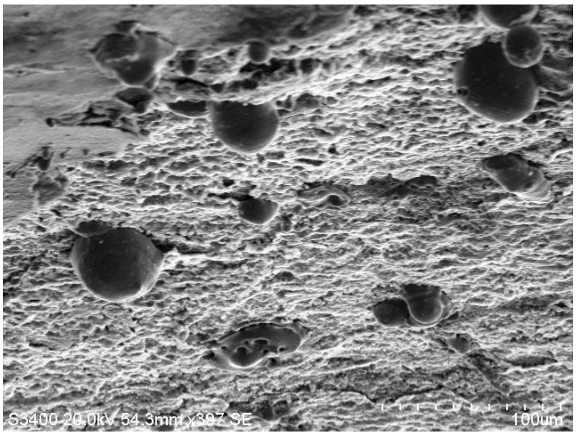
Figure 11 : Scallops typical of FAC as observed on the failed sample of HRSG II.

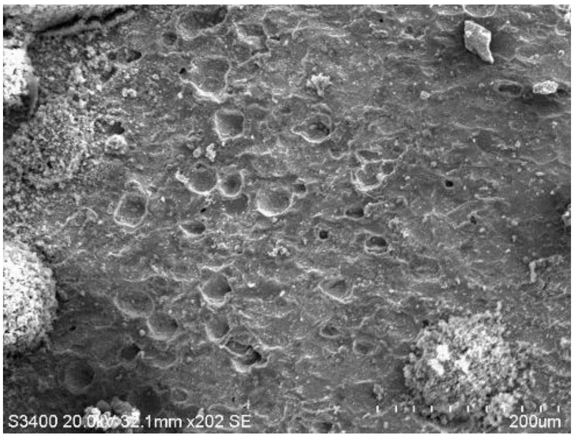
SEM observation of the etched specimen prepared from the transverse section of tube sample revealed distinctly the intergrannular metal loss in the decarburized region both for HRSG I (Figure 12) and HRSG II (Figure 13).





Figures 12 and 13: Decarburization and intergrannular metal loss as observed on the etched specimen of the tube samples of HRSG-I and II.





Figures 14 and 15: Metal loss in the form of pits on the tube surfaces of HRSG-I and II as observed under SEM**.**

The SEM study revealed features typical of flow assisted corrosion (FAC) attack on the tube samples of HRSG-I and II. The etched samples prepared for metallography were observed under SEM and decarburization and removal of grains in intergranular manner were also observed (Figures 12 &13). Metal loss in the form of pits was also observed on the tube surfaces of HRSG-I and II (Figures 14 & 15).

CONCLUSIONS

From the laboratory investigations it was found that the tube surfaces of the HRSG-I and II had morphology indicative of flow accelerated corrosion and erosion attack. Corrosion product analyses showed the presence of several ions deposited on the internal surface of the tubes. These deposits acted as an insulator and excessive deposits prevented efficient heat transfer through the tubes to the water. Prolonged exposure of the tubes under insulation had resulted in the microstructural changes in both external and internal surfaces of the tubes. Due to prolonged heating of tubes at the sub critical temperature range, spherodization of the pearlite had taken place which deteriorated the mechanical properties of the steel. Internal as well as external surface of the tubes was decarburized and gave rise to intergrannular metal loss.

In the case of the tubes of HRSG-II, FAC in consonance with similar microstructural changes resulted in the direct removal of iron from the internal surface of the tube. These metal particles in turn became abrasive to internal surfaces and potentially accelerated the rate of metal loss from the tube surface by erosion which consequently led to its failure.

The tubes of the HRSG I are susceptible to failure under FAC and erosion in a manner similar to the failed tubing of HRSG II, as inter-granular metal loss, and similar microstructural change were observed in both the tubing. Subsequent to this investigation, the tubes of HRSG-1 also failed in a similar manner to that of the tubes of HRSG II

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