



## STRESS CORROSION CRACKING OF CAGE SUPERHEATER TUBES OF A NEWLY BUILT BOILER

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Masuk Tanggal : 03-11-2017, revisi tanggal : 26-12-2017, diterima untuk diterbitkan tanggal 08-01-2018

### Intisari

Sejumlah pipa penukar panas lanjut pada sebuah ketel uap yang baru dibangun ditemukan bocor selama operasi komisioning yang pertama. Kebocoran terjadi ketika ketel uap baru saja mencapai tekanan 23,7 barg dan temperatur 405 °C dari tekanan dan temperatur operasi yang direncanakan yaitu 53 barg dan 485 °C. Dalam makalah ini dibahas jenis kerusakan dan faktor-faktor yang kemungkinan telah menyebabkan terjadinya kebocoran pada pipa penukar panas lanjut tersebut. Penelitian/pengujian metalurgi telah dilakukan dengan mempersiapkan sejumlah benda uji yang diperoleh dari salah satu potongan pipa yang bocor tersebut. Berbagai pengujian laboratorium telah dilakukan meliputi: uji makro, analisa komposisi kimia, uji metalografi, uji kekerasan dan uji SEM (*scanning electron microscopy*) yang dilengkapi dengan analisis EDS (*energy dispersive spectroscopy*). Hasil penelitian/pengujian metalurgi yang diperoleh menunjukkan bahwa pipa penukar panas lanjut yang bocor tersebut telah mengalami retak korosi tegangan yang disebabkan oleh efek kombinasi antara korosi dan tegangan tarik. Unsur korosif yang kemungkinan dapat menimbulkan terjadinya retak korosi tegangan pada pipa penukar panas lanjut adalah kaustik sodium (Na) dan elemen-elemen lainnya pada tingkatan yang relatif rendah seperti Ca, Cl, S dan P.

**Kata Kunci:** Pipa penukar panas lanjut, retak korosi tegangan, kaustik sodium (Na)

### Abstract

A number of cage superheater tubes of a newly built steam boiler have been leaking during boiler's first start-up commissioning. Leaking occurred when the boiler had just reached a pressure of 23.7 barg and temperature 405 °C from the intended operating pressure of 53 barg and temperature of 485 °C. Type of failure and factors that may have caused the leakage of the cage superheater tube are discussed in this paper. The metallurgical assessment was conducted by preparing a number of specimens from the as received leaked cage superheater tube. Various laboratory examinations were performed including macroscopic examination, chemical composition analysis, metallographic examination, hardness test and SEM (*scanning electron microscopy*) examination equipped with EDS (*energy dispersive spectroscopy*) analysis. Results of the metallurgical assessment obtained show that the leaked cage superheater tubes have been experiencing stress-corrosion cracking (SCC) caused by the combined effect of corrosion and tensile stress. The corrosion agent that may have been responsible for the occurrence of SCC in the tube was mostly due to caustic sodium (Na) and other elements in a lesser extent such as Ca, Cl, S and P.

**Keywords:** Cage superheater tube, stress-corrosion cracking (SCC) caustic sodium (Na)

## 1. INTRODUCTION

The failure of industrial boiler has been a prominent feature in fossil fuel-fired power plants. The contribution of several factors appears to be responsible for failures, culminating in the partial or complete shutdown of the plant. A survey of the literature [1]-[6] pertaining to the performance of steam boilers during the last 30 years shows that abundant cases have been referred to, concerned with the failure of boilers due to fuel ash corrosion, overheating, hydrogen attack, carburization and decarburization, corrosion fatigue cracking, stress-corrosion cracking, caustic embrittlement, erosion, etc.

The majority of forced outages of power boilers are due to premature failure of boiler components [1]-[7]. Boiler tube failures are the main cause of forced outages of power generating units. The contribution of total tube failure can be grouped as furnace water wall tubing 61%, superheater and reheater tubes 20%, and skin casing 19% [7]. The superheater tube is one of the critical components of a power boiler in the production of superheated steam. In this case, an investigation has been carried out on a failed superheater tube in a newly built coal fired power plant. One piece of the failed tube of about 300 mm in length received for conducting the failure analysis. This tube piece was one of a number of cage superheater tubes that had been leaking during boiler's first start-up commissioning when the boiler had just reached a pressure of 23.7 barg and temperature of 405 °C (see Figure 1), where the intended operating pressure and temperature of the boiler was 53 bar and 485 °C, respectively. The original outside diameter and wall thickness of the failed tube were 50.61 and 5.12 mm, respectively. The tube was made of ASME SA-192 a standard specification for seamless carbon steel boiler tubes for high-pressure service, which is typical low carbon steel. According to the plant site information, prior to the first start-up commissioning, the newly built boiler was in idle condition for several months. During in its idle time, the power boiler was provided with some mixing chemicals into its boiler tubes such as NaOH and/or others. The aim was to reduce any formation of internal oxidation/corrosion occurring in the tubes.

The purpose of this metallurgical assessment is to verify the material properties and determine whether the material used for the cage superheater tube met the specification or suitable for its operating condition.



Figure 1. Photograph of cage superheater tubes after the accident showing locations of tube leakages

Furthermore, this assessment is also aimed to establish the type, cause and mode of failure of the leaked superheater tube, and based on the determination some corrective or remedial action may be initiated that will prevent similar failure in the future.

## 2. MATERIALS AND METHOD

In performing this metallurgical assessment, one tube piece of the leaking tube of about 300 mm in length shown in Figure 2 is used and a number of specimens were prepared for laboratory examinations. Macroscopic examination on surface damage of the cage superheater tube performed using a stereo microscope, whereas chemical analysis carried out using an optical spark emission spectrometer. The purpose of this chemical analysis was to determine whether the material used for the cage superheater tube met the specification. Metallographic examinations also performed using an optical light microscope at various magnifications. The metallographic specimens were mounted using epoxy and prepared by grinding, polishing and etching. The etchant used was 5% Nital solution. A hardness survey also carried out on the same specimens for the metallographic examination using Vickers hardness method at a load of 5 kg (HV 5). Moreover, examination on some surface fracture of the leaked superheater tube also performed using a SEM (scanning electron microscopy) to determine the surface damage topography and nature of the failure. This SEM examination was also equipped with an EDS (energy dispersive spectroscopy) analysis to detect the presence of any corrosion by-product.

### 3. RESULTS AND DISCUSSION

#### 3.1 Macroscopic Examination on Fracture Surface of the Leaked Superheater Tube

The as-received tube section shown in Figure 2 revealed longitudinal cracks on both sides of the tube. As seen in Figure 2, the

cracks length on the tube surface that facing to the insulation wall (wall side) was about 66 mm, whereas on the tube surface that facing to the fire side, its crack length was about 117 mm.

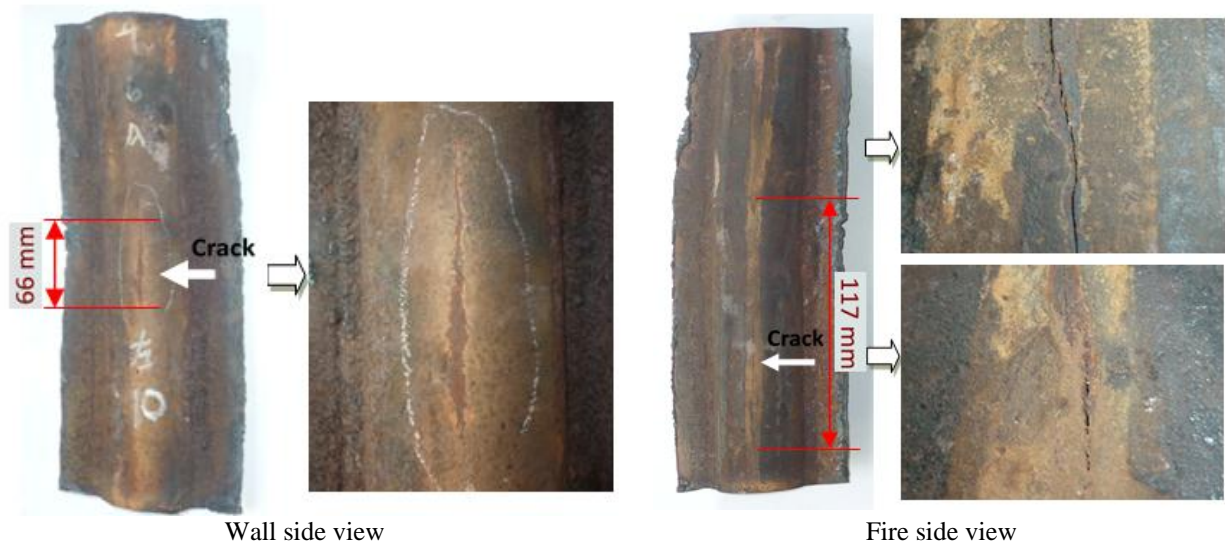


Figure 2. The as-received leaked cage superheater tube

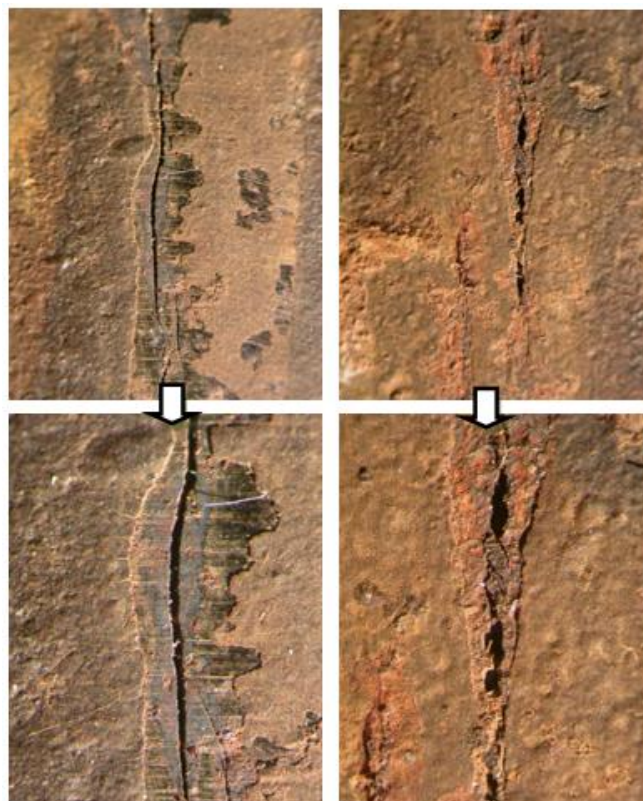


Figure 3. Macroscopic view of some longitudinal cracks area obtained from the external surface of the tube shown in Figure 2



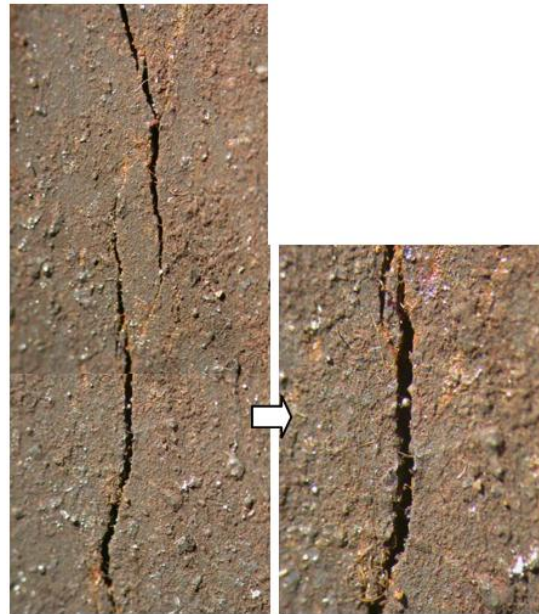


Figure 4. Macroscopic view of some longitudinal cracks area obtained from the internal wall of the tube shown in Figure 2

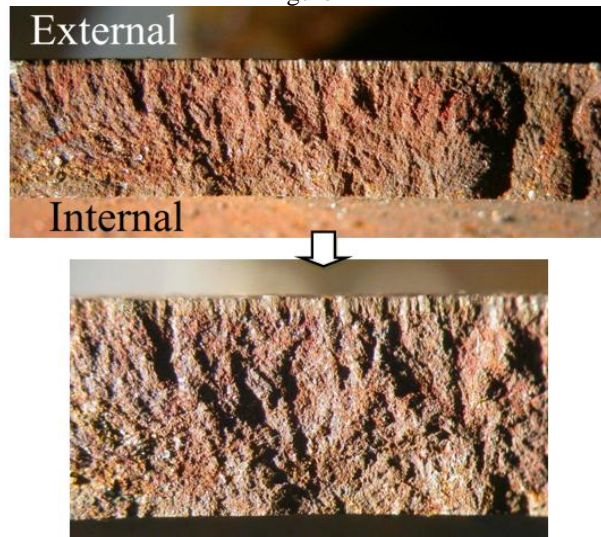


Figure 5. Fracture surface of the fire side tube portion

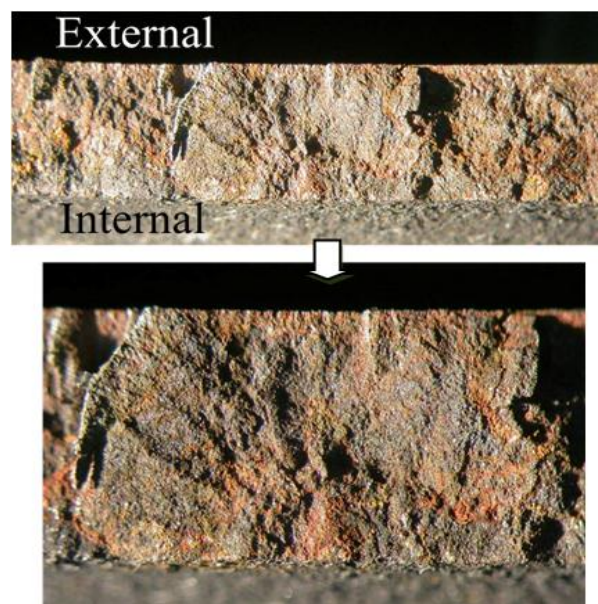


Figure 6. Fracture surface of the wall side tube portion

The cracks on the external tube surfaces were originally coming from the cracks formed on the internal wall of the tube. Enlargement of some longitudinal cracks that formed on the external surface of the tube at the fire side position is shown in Figure 3. Some fireside deposits also observed to have formed on most of the tube external surface. There also seen in Figure 4 that the tube internal wall slightly covered by some deposits. One section of the fire side tube portion was cut away for macroscopic examination and fracture surface of the fire side tube portion obtained from some longitudinal cracks are presented in Figure 5, showing brittle fracture appearance with the cracks were originated from the internal wall of the tube where pits were present [8]-[10]. In addition, one section of the wall side tube portion was also cut away for macroscopic

examination and fracture surface of the wall side tube portion obtained from some longitudinal cracks are presented in Figure 6 showing brittle fracture appearance with the cracks were originated from the internal wall of the tube where pits were present.

### 3.2 Chemical Composition Analysis

Results of chemical analysis obtained from the three different specimens of the leaked tube are presented in Table 1. As seen in Table 1, the tube material is made of a low carbon steel, which may be approximately close to the material specification of ASME SA-192, a standard specification for seamless carbon steel boiler tubes for high pressure service [11].

Table 1. Results of chemical analysis obtained from the tube material in comparison with the standard material

Composition, wt %					
Element	Sample 1	Sample 2	Sample 3	Average	Standard Material (ASME SA-192)
Fe	Balance	Balance	Balance	Balance	Balance
C	0.195	0.178	0.198	0.190	0.06 - 0.18
Si	0.227	0.223	0.231	0.227	0.25 (max)
Mn	0.496	0.505	0.490	0.497	0.27 - 0.63
P	0.020	0.019	0.019	0.019	0.048
S	0.027	0.022	0.023	0.024	0.058
Cu	0.092	0.093	0.096	0.094	-
Al	0.004	< 0.002	< 0.002	0.003	-
Cr	0.055	0.055	0.054	0.055	-
Mo	< 0.002	< 0.002	< 0.002	< 0.002	-
Ni	0.025	0.023	0.023	0.024	-

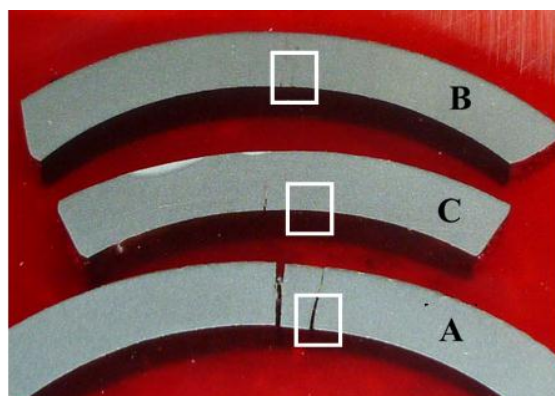


Figure 7. Three specimens A, B and C at different locations were prepared from the leaked tube at its fire side position for metallographic examination



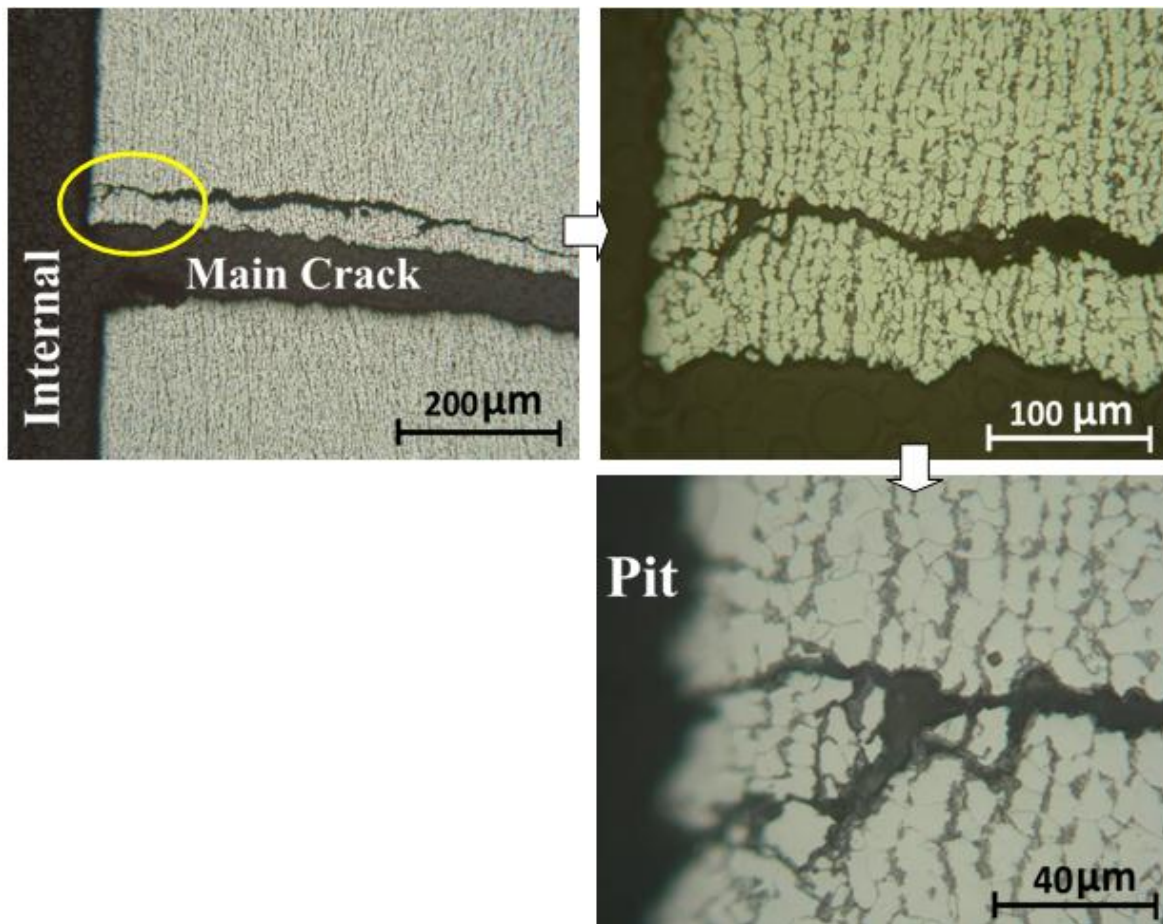


Figure 8(a). Microstructures of sample A obtained from the fire side position of the tube at location as indicated by the square grit in Figure 7, showing ferrite phase as matrix and pearlite as second phase typical of a low carbon steel tube. All the cracks obviously originated from the internal wall of the tube where the corrosion pits were present. The cracks propagated toward the external surface of the tube through the pearlite phase and/or ferrite grain boundaries, typical of stress-corrosion cracking (SCC). Etched with 5% Nital solution

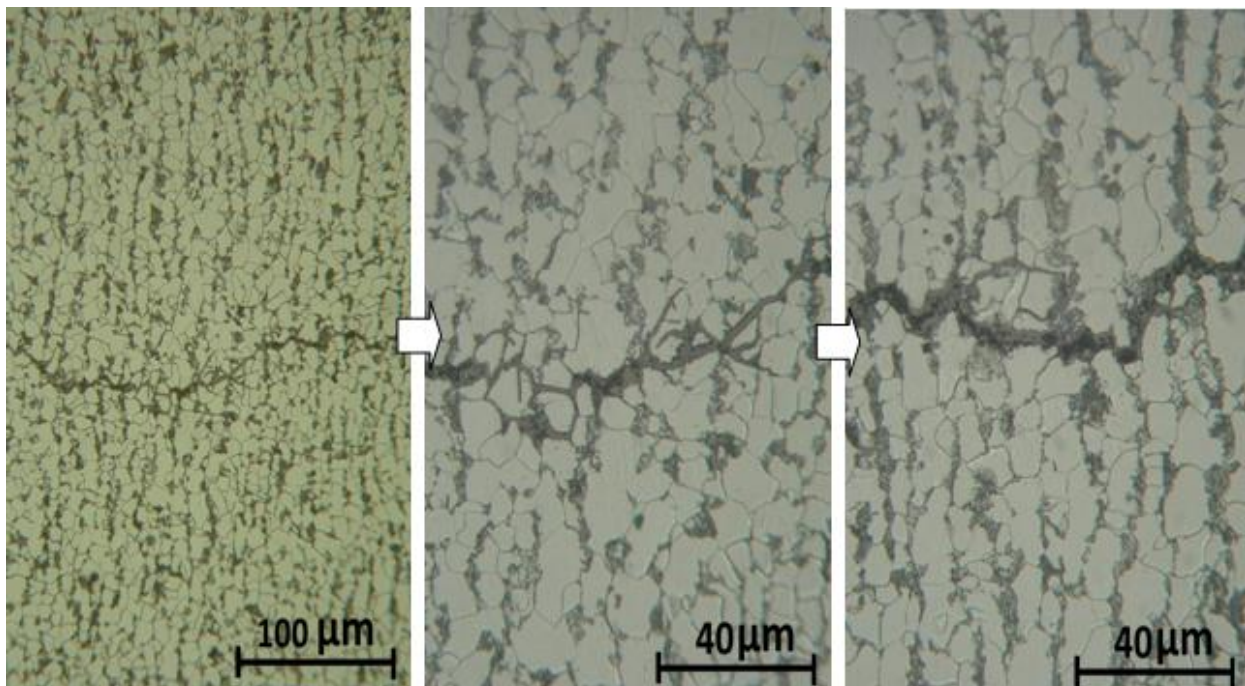


Figure 8(b). Microstructures of sample A shown in Figure 7 obtained from the fire side position of the tube at location around the middle of tube thickness, continued. Etched with 5% Nital solution



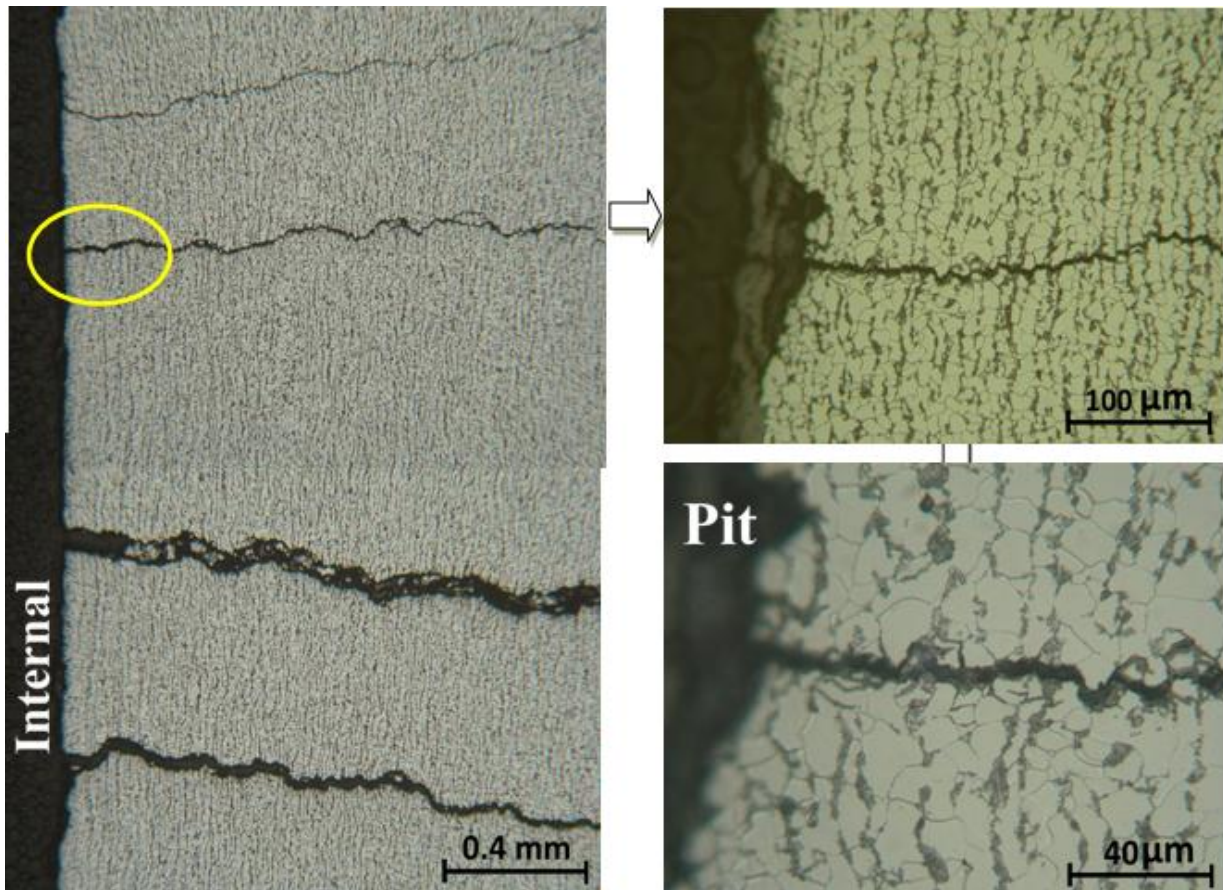


Figure 9. Microstructures of sample B obtained from the fireside position of the tube at location as indicated by the square grit in Figure 7, showing ferrite phase as matrix and pearlite as second phase typical of a low carbon steel tube. All the parallel cracks obviously originated from the internal wall of the tube where the corrosion pits were present. The cracks propagated toward the external surface of the tube through the pearlite phase and/or ferrite grain boundaries, typical of stress-corrosion cracking (SCC). Etched with 5% Nital solution

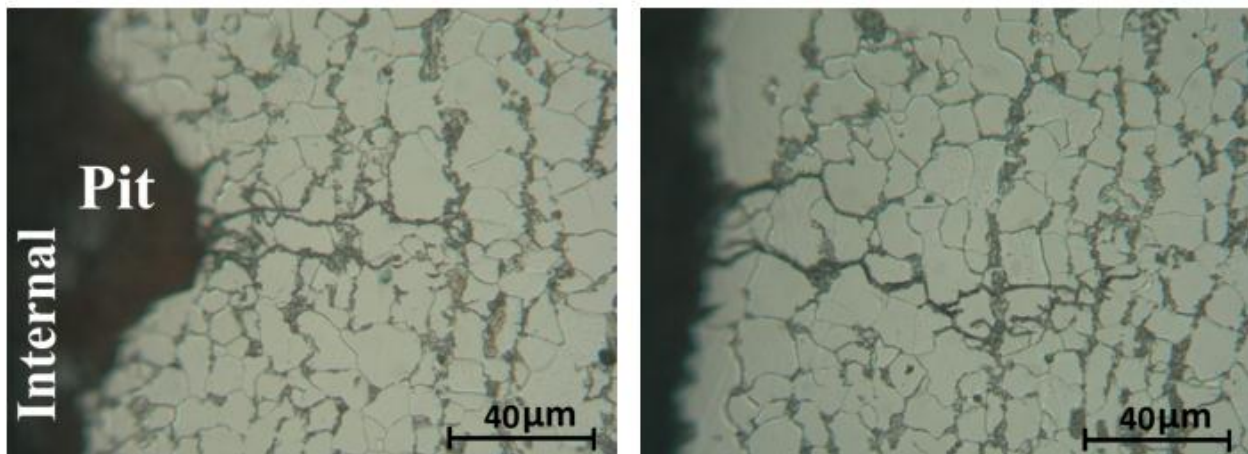


Figure 10. Microstructures of sample C shown in Figure 7 obtained from the fire side position of the tube at location as indicated by the square grit. Etched with 5% Nital solution

#### 4. Results of Metallographic Examination and Hardness Test

Three different specimens in transverse cross section (A, B and C) were cut away from the leaked tube piece at the fire side position (see Figure 7), and the microstructures obtained are presented in Figures 8, 9 and 10. All the microstructures of samples A, B and C obtained

from the fire side position of the leaked tube piece exhibited ferrite phase as matrix and pearlite as second phase typical of a low carbon steel tube. As also clearly seen in Figures 8-10, all the cracks originated from the internal wall of the tube where the corrosion pits present. The cracks propagated toward the external surface of the tube through the pearlite phase

and/or ferrite grain boundaries, typical of stress-corrosion cracking (SCC). Formation of this SCC was most likely caused by the combined effect of corrosion and tensile stress [8]-[10]. The corrosive agent that may have been responsible in causing the SCC in the superheater tube under study will be shown later from the results of SEM/EDS analysis. Whereas formation of high tensile stresses occurred on both tube surfaces that were located at approximately 180° from one side to the other side of tube may have been affected by some hot spots that could produce different thermal expansion or deformation on the tube and resulted in high tensile bending stresses generated at the internal wall of the tube. In addition, the total tensile stresses occurred on the internal tube surface was also affected by the circumferential tensile stress due to the internal working pressure in the tube.

Two other specimens in transverse cross section (D and E) were also cut away from the leaked tube piece at its wall side position (see Figure 11), and the microstructures obtained are presented in Figures 12 and 13. All the microstructures of samples D and E obtained from the wall side position of the leaked tube piece also exhibited similar microstructures as obtained from samples A, B and C at the fireside position of the leaked tube piece. The tube material microstructures consisted of matrix ferrite phase with pearlite second phase. Similarly, all the cracks formed in samples D and E were also typical of stress-corrosion cracking (SCC), originated from the corrosion pits that were present at the tube internal wall and propagated toward the external surface of the tube by cracking through the pearlite phase and/or ferrite grain boundaries.

Hardness test results obtained from samples A, B and C of the fire side tube portion are presented in Table 2 and the average hardness value obtained was 163.1 HV or 154.0 HB, which is equivalent to the tensile strength about 53.9 kgf/mm<sup>2</sup> or 529.3 MPa. Whereas hardness test results obtained from samples D and E of the tube portion located at its wall side presented in Table 3 and the average hardness

value obtained was 153.7 HV or 145.5 HB, which is equivalent to the tensile strength about 50.9 kgf/mm<sup>2</sup> or 500.1 MPa. From the hardness values obtained in Tables 2 and 3 indicated that the mechanical property of the leaked cage superheater tube is well above the material specification of ASME SA-192 with minimum tensile strength of 320 MPa [11].

## 5. SEM Fractography and EDS Analysis

SEM photographs of some fracture surface of sample obtained from the fire side tube portion are presented in Figure 14 and the corresponding EDS spectrum of elements are presented in Figure 15. Most of the SEM photographs obtained obviously exhibited brittle fracture appearance and covered by some deposits. Most of the EDS spectrum of elements obtained from some deposits formed in the corrosion pits around the internal wall of the tube contained trace elements such as: Na, Ca, Cl, S and some P. Furthermore, SEM photographs of some fracture surface of sample obtained from the tube portion located at its wall side presented in Figure 16 and the corresponding EDS spectrum of elements obtained presented in Figure 17. Similarly, most of the SEM photographs shown in Figure 16 obviously exhibited brittle fracture appearance. Also, most of the EDS spectrum of elements obtained in Figure 17 from some deposits in the corrosion pits around the internal wall of the tube contained trace elements such as: Na, Ca, Cl and S [8-10].

From the results of SEM fractography and EDS analysis obtained it showed that the corrosive agents that may have been responsible to the occurrence of stress-corrosion cracking (SCC) in the tube was mostly due to caustic sodium (Na) and other trace elements in lesser extent such as Ca, Cl, S and P. This condition indicated that the leaked tube(s) were most likely experiencing some caustic related embrittlement which is a form of stress-corrosion cracking characterized by surface initiated cracks that occur in tubing exposed to caustic [8]-[10].



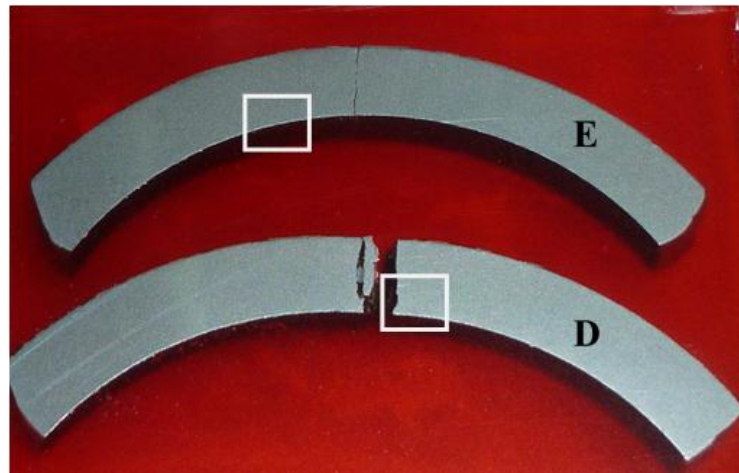


Figure 11. Two tube specimens D and E at different locations were prepared from the leaked tube at the wall side position for metallographic examination

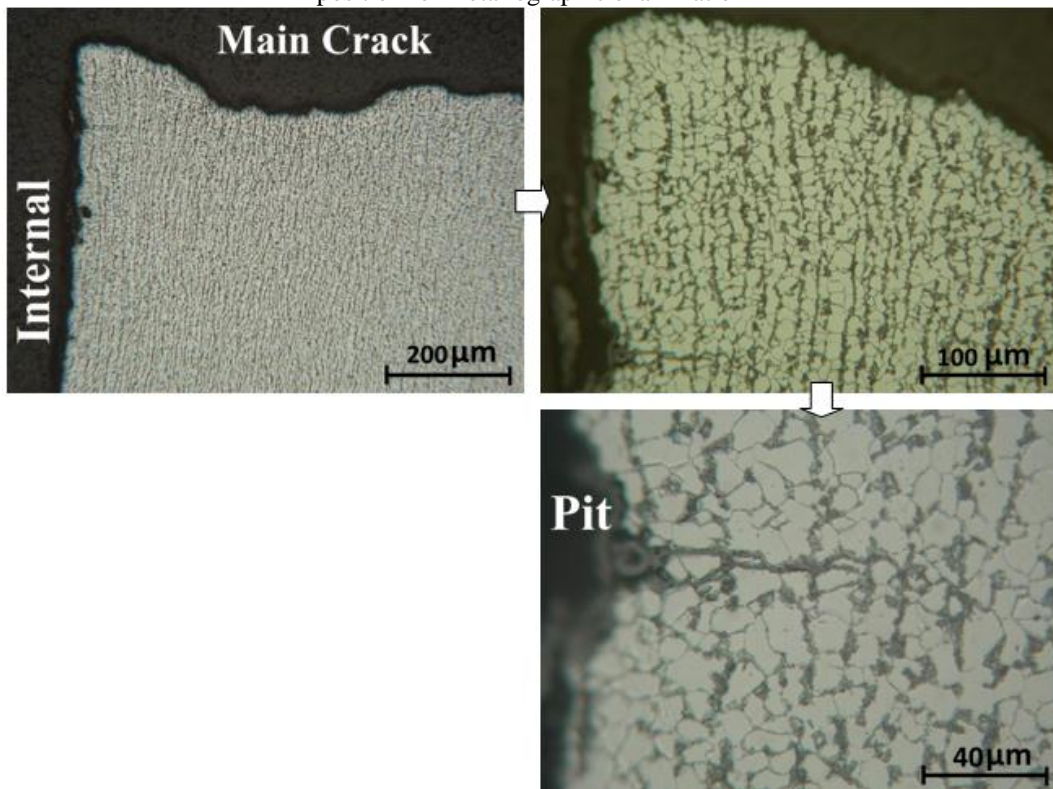


Figure 12. Microstructures of sample tube D obtained from the wall side position of the tube at location as indicated by the square grit in Figure 11. Etched with 5% Nital solution

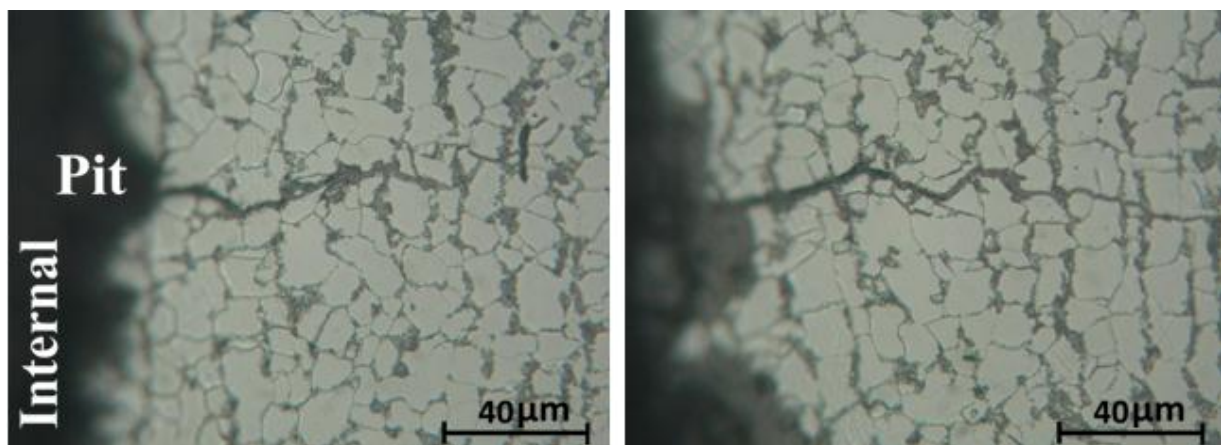


Figure 13. Microstructures of sample tube E obtained from the wall side position of the tube at location as indicated by the square grit in Figure 11. Etched with 5% Nital solution

Table 2. Hardness test results (VHN) of cage superheater obtained from of the fireside tube portion

Test Point	Hardness Value, VHN			
	Sample Tube			
	C	A	B	
1	167.5	164.0	190.0	<b>Average Hardness: 163.1 VHN or 154.0 BHN</b>
2	153.0	147.0	181.0	
3	154.5	149.5	167.5	
4	167.5	152.0	192.0	
5	161.0	144.0	175.0	
6	159.5	144.0	166.0	
Average	160.5	150.1	178.6	

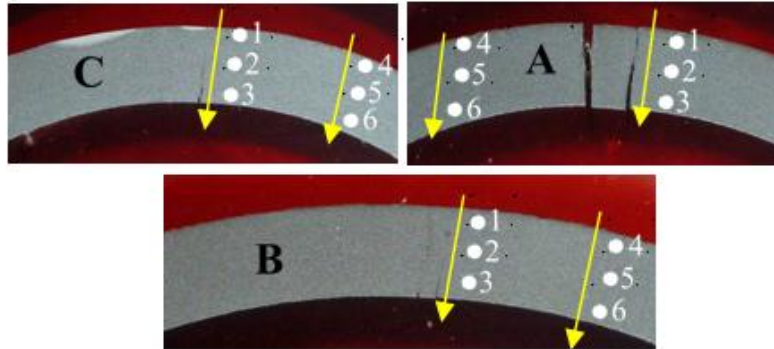


Table 3. Hardness test results of cage superheater obtained from of the wall side tube portion

Test Point	Hardness Value, VHN		
	Sample Tube		
	E	D	
1	162.5	161.0	<b>Average Hardness: 153.7 VHN or 145.5 BHN</b>
2	153.0	148.0	
3	152.0	147.0	
4	158.0	165.0	
5	153.0	156.0	
6	140.6	148.0	
Average	153.2	154.2	

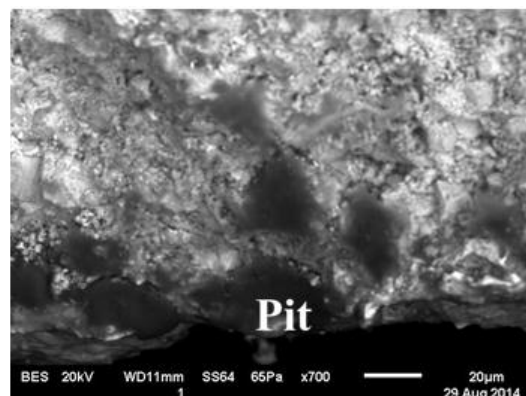
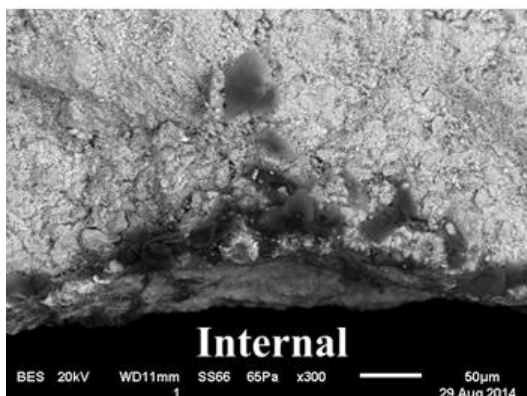


Figure 14. SEM photographs of some fracture surface of cage superheater obtained from the fire side tube portion

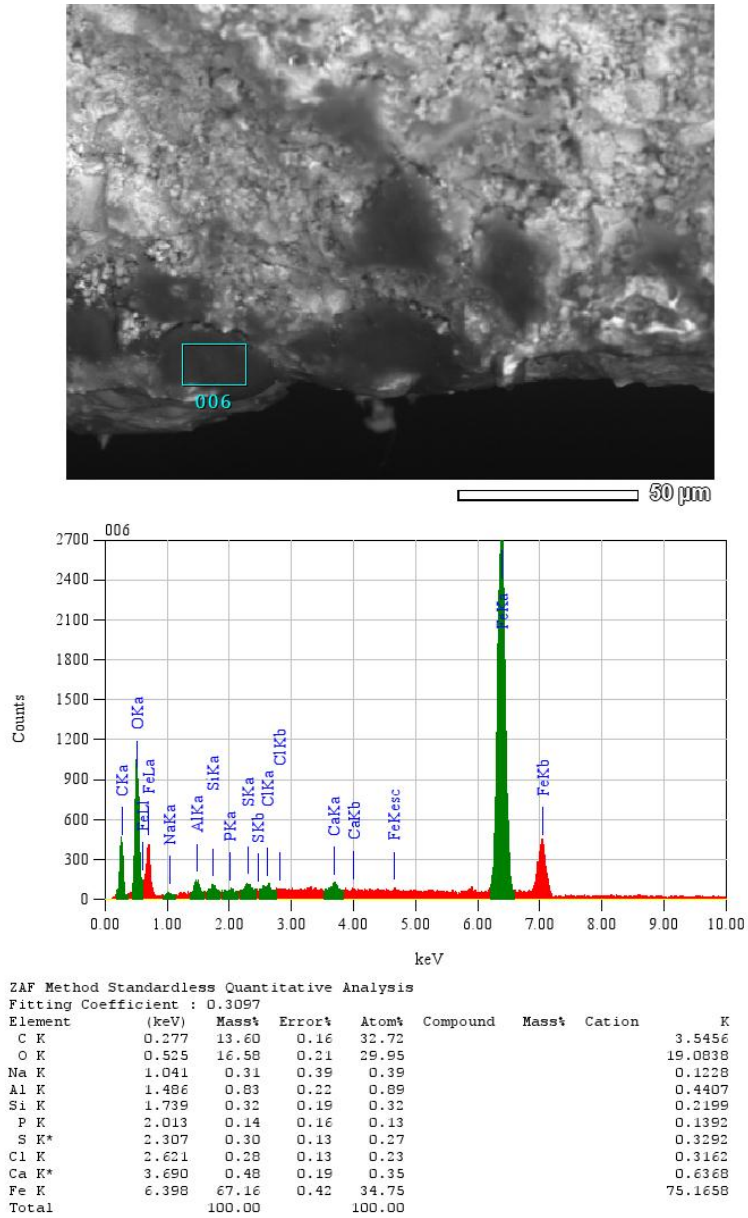


Figure 15. EDS spectrum of elements of some fracture surface of cage superheater obtained from the fire side tube portion

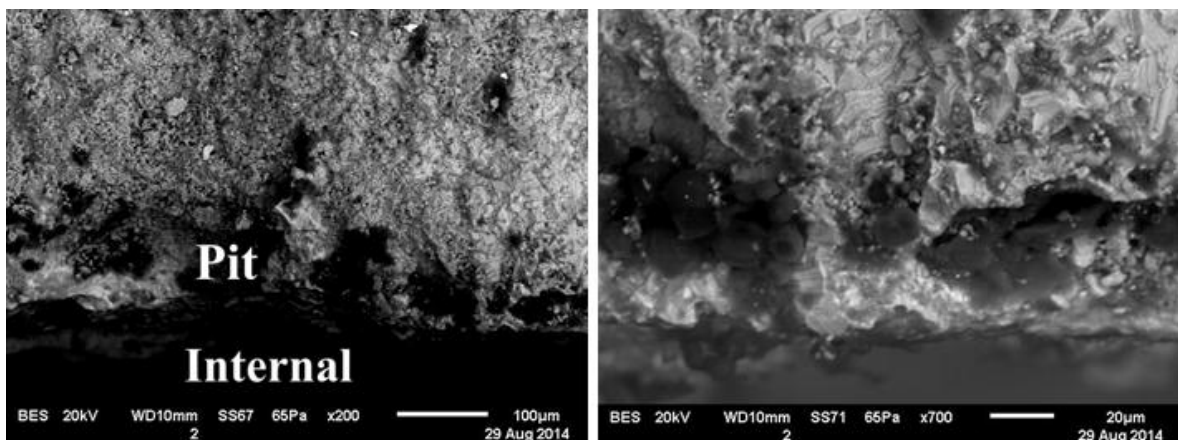


Figure 16. SEM photographs of some fracture surface of cage superheater obtained from the wall side tube portion



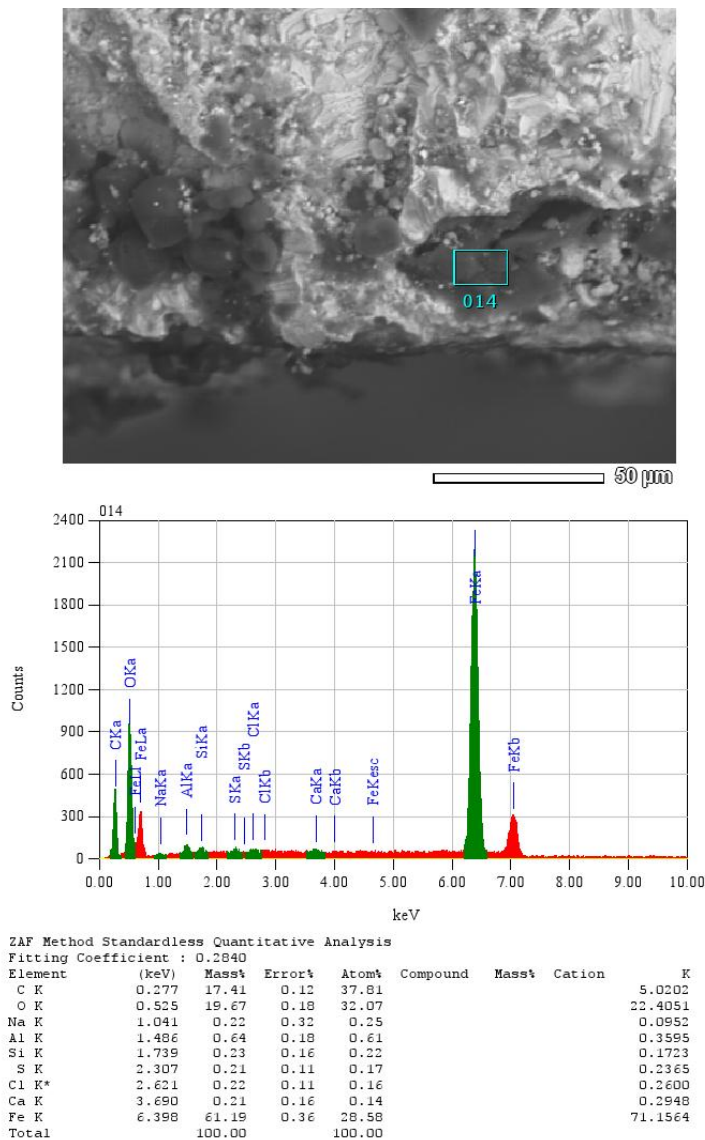


Figure 17. EDS spectrum of elements of some fracture surface of cage superheater obtained from the wall side tube portion

## 6. CONCLUSIONS

The results of chemical analysis obtained show that the material used for the cage superheater tube under study is very much close and met to the material specification of ASME SA-192, a standard specification for seamless carbon steel boiler tubes for high-pressure service.

It is also observed that all the specimens obtained from the leaked cage superheater tube exhibit similar microstructures of ferrite phase as matrix and pearlite as second phase typical of a low carbon steel tube. In addition, the average hardness value obtained from all the specimens of the leaked cage superheater tube have similar hardness value in the range of 145.5 to 154.0 HB or equivalent to tensile strength of 500.1 to 529.3 MPa. This indicated that the mechanical property of the leaked cage superheater tube is well above the material

specification of ASME SA-192 which its minimum tensile strength 320 MPa.

According to the crack topography and mode of failure, the leaked tube(s) had experienced predominantly to stress-corrosion cracking (SCC) caused by the combined effects of corrosion and tensile stress. Most of the cracks occurred initiated at the internal wall of the tube where high level of tensile stresses and corrosion pits were present. Cracks propagation rates may have increased dramatically as the tube metal temperature increased during the boiler's start-up operation.

The corrosive agents that may have been responsible for the occurrence of SCC in the tube were mostly due to caustic sodium (Na) and other elements in a lesser extent such as Ca, Cl, S and P. This indicated that the leaked tube had experienced some caustic related embrittlement.

Since the cracks growth through wall of the tube was in a matter of hours during the boiler's start-up operation, this also indicated that the caustic concentration was probably high resulting from alternating wet and dry conditions and/or localized hot spots. Most likely, this condition occurred due to over-firing resulting in formation of steam blanketing, especially in the vertical tubes.

Formation of high tensile stresses on both tube surfaces may have occurred at location approximately 180° from one side to the other side of tube. This may have been affected by some hot spots occurred and could produce different thermal expansion or deformation on the tube and resulted in high tensile bending stresses generated at the internal wall of the tube. In addition, the total tensile stresses occurred on the internal tube surface was also affected by the circumferential tensile stress due to the internal working pressure in the tube.

#### ACKNOWLEDGEMENT

The author wishes to express his gratitude to the Head and Members of Department of Mechanical Engineering, Faculty of Industrial Technology of the National Institute of Science and Technology (ISTN) for their support and encouragement in publishing this work.

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