

FAILURE ANALYSIS OF A SUPERHEATER  
TUBE OF A COAL-FIRED POWER PLANT

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UNIVERSITI TUN HUSSEIN ONN MALAYSIA

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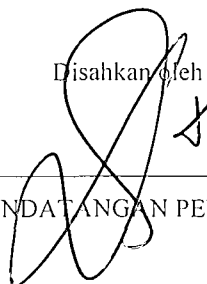
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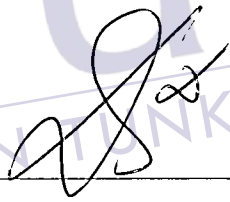
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**FAILURE ANALYSIS OF A SUPERHEATER TUBE OF A COAL-FIRED  
POWER PLANT**

**SALUSTIANO DOS REIS PIEDADE**

**A thesis submitted in  
fulfillment of the requirements for the award of the  
Degree of Master of Mechanical Engineering**

**Faculty of Mechanical and Manufacturing Engineering  
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**JUNE 2008**



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In the name of God, the most gracious, the most merciful

With the highest praise to God that I manage to complete this projects successfully. I would like to extend my sincere gratitude to my project supervisor, Assoc. Prof. Dr. - Ing. Ir. Darwin Sebayang and Dr. Syahril D.I.C. for their assistance and inspiration towards the progress of this project. Throughout the year, my supervisor has been patiently monitoring my progress and guided me in right direction and offering encouragement.

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## ABSTRACT

Failure analysis of structures has gained a considerable interest in many engineering areas. The aim of this research is to determine the root cause of the structural failures which can reduce the failure risks and prevent similar failures in the future. This thesis presents experimental investigations for the failure of a superheater tube of a coal-fired power plant using several failure analysis procedures. The failure analysis comprised of visual inspection, optical microscopic, scanning electron microscopy combined with the energy dispersive X-ray spectroscopy (EDS) and energy dispersive X-ray diffraction (EDXD). A sample of a total-fractured superheater tube obtained from an industry was used in this investigation. Initial visual investigations found that the superheater tube had a longitudinal crack. This fracture appearance is called fish mouth stress rupture. The specimen was initially cut, mounted, grinded, polished and etched. A significant oxide layer of 1.75mm in thickness was occurred in the steam side surface. The optical microscopy and scanning electron microscopy were used to identify intergranular cracks, voids, elongated grain and deposit layers. The EDS and EDXD were used to identify types and compositions of the oxide substances. The results revealed that the steam and fire side surfaces consist of sodium iron oxide, hematite and magnetite. The study also demonstrates that the superheater tube of a coal-fired failed due to creep mechanism. This resulted in overheating problem inside the tube; caused by deposit layers, which contributes to the creep mechanism. Periodically cleaning and maintenance should be done in order to avoid accumulation of deposit layers.



## ABSTRAK

Analisis kegagalan struktur merupakan suatu elemen penting dalam pelbagai bidang kejuruteraan. Kajian ini dijalankan untuk menentukan punca kegagalan sesuatu struktur bagi mengurangkan risiko kegagalan seterusnya menghindarkan kegagalan serupa daripada berulang. Tesis ini menjelaskan hasil kajian eksperimen yang dijalankan ke atas struktur tiub panas lampau sebuah loji kuasa arang batu menggunakan beberapa prosedur analisis kegagalan. Ini merangkumi kaedah pemerhatian, mikroskop optik, mikroskop pengimbas elektron dengan spektroskop X-ray serakan tenaga (EDS) dan pembelauan X-ray serakan tenaga (EDXD). Sampel bahan kajian yang digunakan adalah merupakan sebatang tiub panas lampau sebuah loji kuasa yang telah pecah. Pemerhatian visual telah mendapati bahawa tiub panas lampau telah mengalami keretakan membujur. Kegagalan ini dikenali sebagai "*fish mouth stress rupture*". Spesimen ini perlu terlebih dahulu melalui proses pemotongan, pemesinan, pencanaian, penggilapan dan punaran. Lapisan besi oksida setebal 1.75 mm dikesan di bahagian dalam dinding tiub. Mikroskop optik dan pengimbas elektron telah digunakan untuk mengenalpasti fenomena keretakan antara ira, lompong, pemanjangan ira dan lapisan endapan. Mikroskop EDS dan EDXD telah digunakan untuk menentukan jenis dan komposisi bahan oksida. Hasil kajian menunjukkan bahawa di bahagian permukaan dalam dinding tiub mengandungi sodium iron oksida, hematite and magnetite. Kajian juga memperlihatkan bahawa kegagalan tiub panas lampau sebuah loji kuasa arang batu berpunca dari mekanisma rayapan. Lapisan endapan yang wujud menyebabkan fenomena masalah panas lampau di dalam tiub yang menyumbang kepada mekanisma rayapan. Proses penyelenggaraan dan pembersihan tiub harus dilakukan secara berkala bagi mengelakkan pengumpulan lapisan endapan.

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## CHAPTER I

### INTRODUCTION

#### 1.1 Introduction



Failure analysis is an engineering approach to determining how and why equipment or a component has failed [1]. The goal of a failure analysis is to understand the root cause of the failure so as to prevent similar failures in the future. The cause of failure can play a role in establishing liability in litigation. Failure analysis is important to determine the original, proximal cause of a failure.

Failure analysis of boiler tube is important to understand the root cause of the failure in terms of both the material of the tube and the boiler operation. There are many types of approaches in analysis of the boiler tube failures. However, estimation can be made on the capability of tubes and thus simply boiler time of failure. The results and finding should be able to identify the cause of failure and indicate the type of mode failure at the respective failure region.

## 1.2 Statement of Problem

As received one piece of superheater tube from industry with ASME specification SA-213-T22 grade steel. The superheater tube has undergone five years of service. The normal operation temperature of this tube was 540 °C and the type of the firing was coal-fired. The received superheater tube was completely fractured. Therefore the problem is to know what cause of fracture superheater tube.

## 1.3 Objective of Study

There are three primary objectives of this study. The first objective is to examine the evidence presented by the superheater tube failure and from that evidence, determine the failure mechanism. The second objective is to determine the root cause of the failure. The third objective is to recommend corrective measures that can prevent similar failures.

## 1.4 Scope of Study

The scope of this study is as follows:

1. Collect failure mode inventory of the fractured boiler tube.
2. Sample investigation conducted by optical microscopy (OM), scanning electron microscopy (SEM) combined with energy dispersive X-ray spectroscopy (EDS) and energy dispersive X-ray diffraction (EDX).
3. Analyze the investigation results in the cause of fractured superhater tube.

4. The findings results of superheater tube fracture will be compared with unused tube sample and failure mode inventory.



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## CHAPTER II

### LITERATURE REVIEW

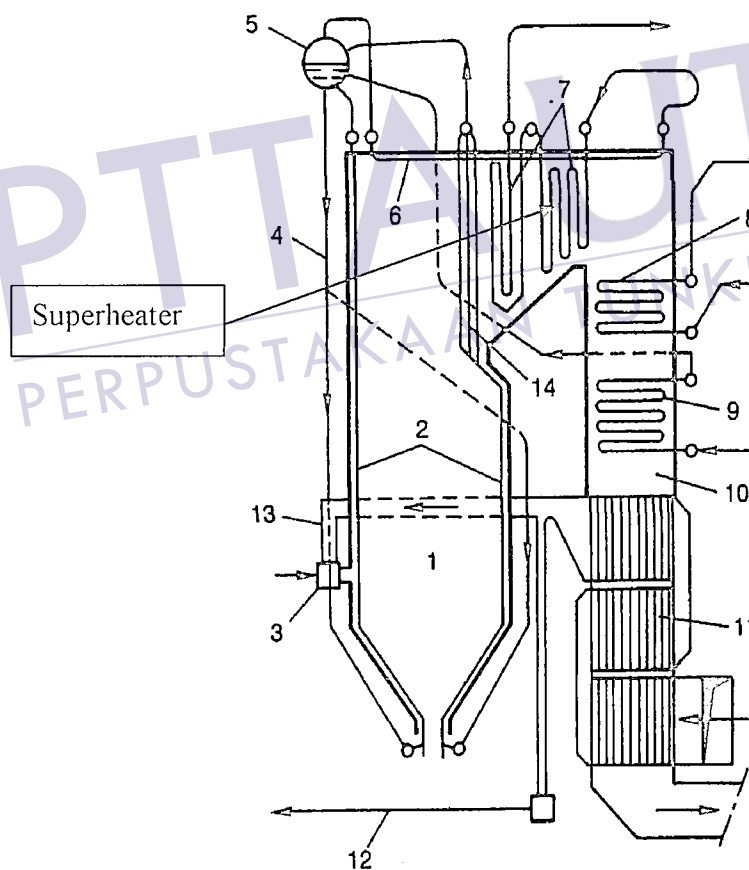
#### 2.1 Introduction

Superheaters in utility boilers increase the temperature of saturated or near-saturated steam in order to increase thermodynamic efficiency of the power cycle or provide the desired process conditions. In general terms, they are simple single phase heat exchangers with steam flowing inside the tubes and flue gases passing the outside the tubes, generally in cross flow Figure 2.1 [2]. Platen superheaters are generally exposed to high temperature and pressure particularly at tip sections where the flue gas temperature may rise to more than 1000 °C [3]. With a steam temperature of 540 °C inside the tube the outer metal temperature may exceed 600 °C. Tube materials may vary from carbon steel to low Cr ferrite to austenitic stainless steel. Superheater tubes under operating condition are very much prone to the formation of oxides on both inner and outer layers. Initially the outer oxide layer is essentially Fe<sub>3</sub>O<sub>4</sub> type and inside the tube is a spinel-type oxide containing steel alloying elements. The compositions of the deposit on the outer wall depend on the type and nature of the fuel and the conditions of the combustion. The corrosion of the outer wall is caused by the deposition of sodium and potassium sulphate. Fieldner [4] indicated at least 182 other investigators had examined the fusibility of ash based on



eight fundamental oxides most frequently found in coal ash (i.e.,  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{TiO}_2$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{CaO}$ ,  $\text{MgO}$ ,  $\text{Na}_2\text{O}$ , and  $\text{K}_2\text{O}$ ).

These sulphates gradually accumulate by condensation. If the temperature of the tube surface exceeds  $580^\circ\text{C}$  these sulphates will melt. The thin layer of highly corrosive molten layer, built on the initially formed oxide layer, attacks the oxide scale and forms Fe, Cr and Ni sulphates. It has been pointed out that in many cases a thin protective oxide of  $\text{Fe}_3\text{O}_4$  is deposited on the waterside of the tubes. The protectiveness of this thin layer depends on the pH level of the water and on the amount of contamination [3].



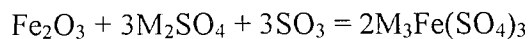
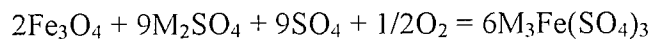
**Figure 2.1:** Flow diagram of the natural –circulation boiler: 1-furnace, 2-water wall, 3-burners, 4-downcomers, 5-drum, 6-radiant superheater, 7-convection superheater, 8-reheaters, 9-economizer, 10-gas duct, 11-air heater, 12-primary air, 13-secondary air [2].

## 2.2 Coal-Fired

Coal of different varieties being is used for big boilers, mostly for industrial and utility boilers. Coal is very economical fuel for using in the boilers for power generation plants. It is an attractive fuel owing to its low price linked to its world wide availability and due to the future shortage of other fossil fuel reserves such oil and gas. But combustion of coal generates very corrosive media particularly near the superheater tubes [5].

Many authors reported that condensation/accumulation of low melting-point salts from flue gas on the boiler tubes used for superheater and reheater is coal fired boilers is a root cause for the severe wastage of tube material. These salts sulfates of sodium and potassium easily liquefy at the operating temperatures and causes severe hot corrosion of boiler tubes [5].

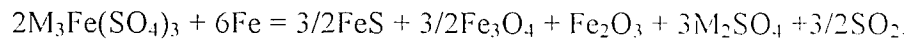
The environment in the coal-fired system consists of ashes and gases at high temperatures and sulfur is considered as the main corrosive elements. According to published literature, the alkali-iron trisulphates  $(\text{Na,K})_3\text{Fe}(\text{SO}_4)_3$  are held responsible for the degradation of coal-fired plant superheaters. These compound stem from the reaction of alkali sulphates with iron oxides (coming from oxide scales or ashes) in the presence of  $\text{SO}_3$  (resulting from the oxidation of  $\text{SO}_2$ ) according to the following reaction [5].



Where M=Na or K

They are molten at operations due to their low melting temperatures; 624 °C for  $\text{Na}_3\text{Fe}(\text{SO}_4)_3$  and 618 °C for  $\text{K}_3\text{Fe}(\text{SO}_4)_3$ , and 552 °C for the mixed compounds  $(\text{Na,K})_3\text{Fe}(\text{SO}_4)_3$ . These molten compounds can take part in fluxing causing

dissolution of the scale or react with metal to form internal sulphids as per reaction given below:



### 2.2.1 Combustion Properties

The combustion of coal is a more complex process than that of oil or gas. It can best be described as a series of processes [6]:

- a) All coal contains some moisture. During the early stages of combustion this moisture is evaporated using some of the coal's energy in doing so.
- b) As the temperature increases, a range of gases including carbon monoxide, methane, and a variety of hydrocarbons, is given off from the coal. However, all of these gases are fuels and carry as much as half of the energy of the coal. They comprise the volatile matter which can be captured and used.
- c) The remaining fixed carbon is effectively charcoal and burns with oxygen from the air to create carbon dioxide.
- d) With all the fuel burnt out, anything left over is ash.

### 2.2.2 Coal Processing

Black coal may be used without any serious processing: other than crushing and screening to reduce the rock to a useable and consistent size. However, it is often washed to remove pieces of rock or mineral that may be present. Washing reduces ash and improves the overall quality of the coal. Coking coal is heated in the absence

of air to produce gases and coke. Coal can also be further processed to produce oil and petroleum products [6].

### 2.3 Boiler Water Treatment

The condition of the boiler feedwater can be critical to both maintenance and efficiency of the boiler. Poor quality water can cause corrosion and inhibit heat transfer. However, the subject of chemical water treatment associated with steam generation is an extremely complex one and will vary greatly with the type and quality of water in each area of the country and also be dependent on the pressure and type of boiler being used. The objects of water treatment are twofold (1) the removal of suspended and soluble solids and (2) the removal of gases [7]. Water treatment should reduce to minimum or absolutely prevent the following undesirable and dangerous conditions: foaming, scale formation and corrosion.

The formation of scale on boiler heating surface is the most serious problem in steam generation. The object of the process for treating water before it enters the boiler is to reduce the amount of scale and sludge-forming deposits. However, since no external treatment, regardless of efficiency, can remove all harmful chemicals, we must provide internal treatment to boiler water.

The primary cause of scale formation is a decrease in solubility of the salts accompanying an increase in temperature. Consequently, the higher the temperature and pressure in a boiler, the more insoluble are the scale-forming salts [8]. Deposits in boiler tubes can reduce circulation through tubes. This may enhance further deposit formation due to the reduction of the cleansing effect of circulating water on solids concentrating at heat transfer surface [9]. The inside diameter deposit layer is produced by oxidation in the boiler tube. The layer build up occurs when the tubes

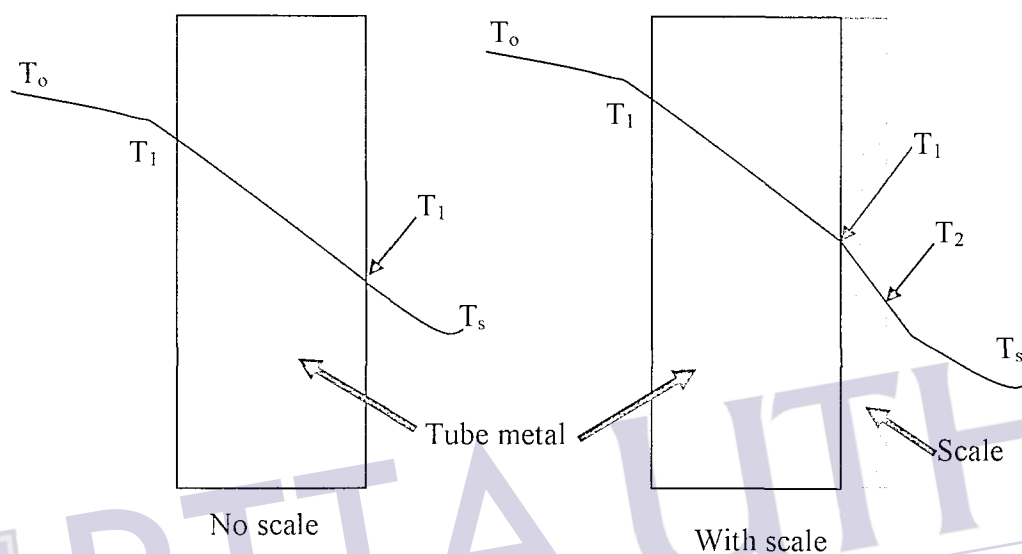
have experienced high temperatures for extended periods of time. The formation of inside diameter layer reduces heat transfer and results in a further increase of tube metal temperature. Higher temperatures promote further growth of inside diameter layer. The result is the inside diameter layer feeds on itself and as it continues to grow, it causes further thinning of the tube.

Inside diameter oxide scale can be produced when tubes in the reheater and superheater have experienced high temperatures for extended periods of time. The formation of inside diameter scale reduces heat transfer and results in a further increase of tube metal temperature. The increase in inside diameter scale and the associated tube metal temperature promotes creep in the tube metal. Formation of creep results in a loss of strength at high temperature. The final outcome of excessive scale is a thick lipped, long term overheats failure [10].

When a tube enters service the metal in contact with the internal steam begins to form a layer of magnetite ( $\text{Fe}_3\text{O}_4$ ) scale. This layer grows thicker in service and its growth over time is dependent on metal temperature. This oxide layer is also a barrier to heat transfer and as its thickness increases; metal temperatures must also increase to maintain a constant outlet steam temperature. Typically, tube metal temperatures increase from 1 to 2F (0.6 to 1.1C) for each 0.001 inch (0.03 mm) of internal oxide formed [11]. Sarver et al [12] and Wreigh et al. [13] state that when the metal temperature is below approximately 580°C (1076°F) and sufficiently high partial pressure of oxidation is present, a double-layer scale consisting of magnetite ( $\text{Fe}_3\text{O}_4$ ) and hematite ( $\text{Fe}_2\text{O}_3$ ) is found on the steam side surface of ferritic alloys. The information of oxide scale can be used to estimate the metal temperature using Larson Parameter;  $\text{Log } X = 0.0002 [T (20 + \log t)] - 7.25$  [11, 14, 15], where X is the scale thickness (in mills); T is the Temperature (in degree Rankin) and t is the operational time (in hours).

But more important is a possible overheating of the boiler metal due to the lack of heat transfer caused by scale deposit. The resultant damage caused by

overheating can result in burned-out tubes and blisters on steam and water drums. Figure 2.2 illustrates the formation of deposit layer of the tube of water/steam surface, where;  $T_0$  is temperature of flue gas,  $T_1$  is temperature of tube metal,  $T_2$  is temperature of oxide scale and  $T_s$  is temperature of steam.



**Figure 2.2:** The temperature profile from flue gas temperature ( $T_0$ ) to steam/water temperature ( $T_s$ ) for the clean tube and the scaled conditions.

### 2.3.1 External Treatment

External treatment is the treatment of water before it enters the boiler. Water treated before it enters the boiler has all or most of the scale forming salts and gasses removed [16]. External treatment usually refers to the chemical and mechanical treatment of the water source. The goal is to improve the quality of this source prior to its use as boiler feed water, external to the operating boiler itself. Such external treatment normally includes: Clarification, filtration, softening, dealkalization, demineralization, deaeration and heating.

### 2.3.2 Internal Treatment

Internal boiler water treatment is treated the water after it has entered the steam and water drum. The boiler water must be treated to prevent scale formation on tubes and heating surface, corrosion of the shell and tubes, caustic embrittlement at seams, and carryover of boiler water into superheater and steam line [16]. Even after the best and most appropriate external treatment of the water source, boiler feed water (including return condensate) still contains impurities that could adversely affect boiler operation. Internal boiler water treatment is then applied to minimize the potential problems and to avoid any catastrophic failure, regardless of external treatment malfunction.

### 2.4 The Standard ASME Specification for Boiler Tubes

American Society of Mechanical Engineers (ASME): Boiler and Pressure Vessel Code construct international requirement in a matter of law, designed, constructed and inspected in term of boiler or any pressurize vessel. The code consists many sections but boiler work requires reference from section I (Power Boilers), section II, Part A, D (Material Properties), Section V (Nondestructive Testing), Section IX (Welding and Brazing), ANSI/ASME B31.1 (Power Piping) and ANSI ASME (National Board Inspection Code-for Repair Work) [17, 18].

Tubes are made under specification, which are commonly made from carbon steel type including SA-178, SA-192, SA-209, SA-210, SA-213, SA-226, SA-250, SA-268 and SA-423. The physical and mechanical properties are listed in Table 2.1. Four common materials can be considered in producing high temperature boiler tube. These are carbon steel, low-Alloy steel, high-Alloy steel, and stainless steel. However in previous times a development of high temperature resistance tube made

from ceramic matrix composites (CMC) were proposed to be a reliable material for boiler tubing [17].

**Table 2.1:** Physical and mechanical properties

ASME Specification	ASME Grade	Mechanical Properties (minimum)					
		Tensile strength		Yield strength		Elongation % 2" or 50 mm	Max. Hardness Rockwell B
		ksi	MPa	ksi	MPa		
SA-178	A	47	324	26	179	35	77
SA-192							
SA-178	C	60	414	37	225	30	79
SA-210	A-1						
SA-210	C	70	483	40	276	30	89
SA-209 and	T1b	53	365	28	193	30	77
	T1	55	379	30	207	30	80
SA-250	T1a	60	414	32	221	30	81
SA-213	T2	60	414	30	207	30	85
	T12	60	414	30	207	30	85
	T11	60	414	30	207	30	85
	T3b	60	414	30	207	30	85
	T22	60	414	30	207	30	85
	T21	60	414	30	207	30	85
	T5	60	414	30	207	30	85
	T5b	60	414	30	207	30	89
	T5c	60	414	30	207	30	85
	T7	60	414	30	207	30	89
	T9	60	414	30	207	30	89
	TP-304	75	517	30	207	35	90
	TP-310	75	517	30	207	35	90
	TP-316	75	517	30	207	35	90
	TP-321	75	517	30	207	35	90
TP-347	75	517	30	207	35	90	
TP-348	75	517	30	207	35	90	



### 2.4.1 Boiler Material Requirements

The boiler tubes in practice conduct flow of heated steam at an elevated pressure from boiler. The material requirement of boiler tube is strength to resist the working pressure, corrosion resistance and oxidation resistance (at temperature above 560°C. As the working fluid moves through the boiler, its temperature rises and the material used becomes progressively more highly alloyed. If temperature does not exceed 425°C (800°F), it is adequate to use carbon or carbon manganese steels for boiler parts. Above this temperature the creep range is encountered and it becomes necessary to consider the low-alloy steel beginning with 1 Cr-0.5Mo and continuing with 2.25 Cr-1 Mo and the more highly alloyed steels.

The Cr 2.25-1Mo steel can be used up to 565°C but beyond this temperature, oxidation resistance becomes more important than creep strength. Corrosion resistance is as important as temperature resistance and the need for this is determined by the nature of the fluids circulating within and around the boiler tubes.

Boiler tubes carry the steam at its maximum temperature and pressure from the boiler. The boiler tube should thereby operate under creep condition and are designed from creep rupture data to last the life of the plant, not less than 100,000 hours. The tube preferred material for temperature up to 540°C is the 0.1Cr-0.5Cr-0.5Mo-0.25V alloy steel. The key components whose performance is critical for ultra supercritical (USC) plants are high pressure steam piping and headers, superheater tubing and water wall tubing. All of them have to meet creep strength requirements. In addition, pipes and headers, being heavy section components, are subject to fatigue induced by thermal stress. Ferritic/martensitic steels are preferred because of their lower coefficient of thermal expansion and higher thermal conductivity compared to austenitic steels.

Superheater tubing application calls for high creep strength, thermal fatigue strength, weldability, resistance to fireside corrosion/erosion and resistance to steam

side oxidation. Thermal fatigue resistance as well as cost considerations would dictate the use of ferritic/martensitic steels. Unfortunately, the strongest of these steels which can be used up to metal temperature of 620°C (1150 F) purely from a creep strength point of view are still limited by fireside corrosion to metal temperature of 593 °C (1100 °F). This corresponds to a steam temperature of about 565°C since superheater metal temperature can exceed the steam temperature by as much as 28°C (50°F). Excessive corrosion of ferritic steels caused by liquid iron-alkali sulfates in the tube deposits is an acute concern in the USA, where high sulfur corrosive coals are used more frequently than elsewhere. Therefore high strength ferritic stainless steels such as T-91 are infrequently used in US. The standard practice is to use T-22 for lower temperatures and SS304H or SS347 for the highest temperature [19].

## 2.5 Failure Mode Inventory

The objective in this sub section is to make the failure mode inventory of the others researchers which has been carried out in their material investigation. It is used as a reference of present investigation of boiler of superheater tube failures.

### 2.5.1 Causes of Boiler Tube Failures

The boiler tube failures often occur in the superheaters of a utility boiler, after the boiler has operated for a period of time. This boiler tube failure seriously affects the economic and safe operation of the utility boiler. Some of the common failures associated with boilers are pitting, erosion, stress corrosion cracking, hydrogen

damage, stress rupture, corrosion fatigue, thermal fatigue, over temperature, and maintenance damage [1].

### **2.5.1.1 Failure Caused by Corrosion**

Corrosion is result of low-alkaline boiler water, the presence of free oxygen, or both. The boiler metal is converted into red or black powder (iron oxide) which is readily washed away by the water. This action is accelerated at points of greatest stress and as the corrosion proceeds, the metal thickness is reduced and the stress is further increased [20].

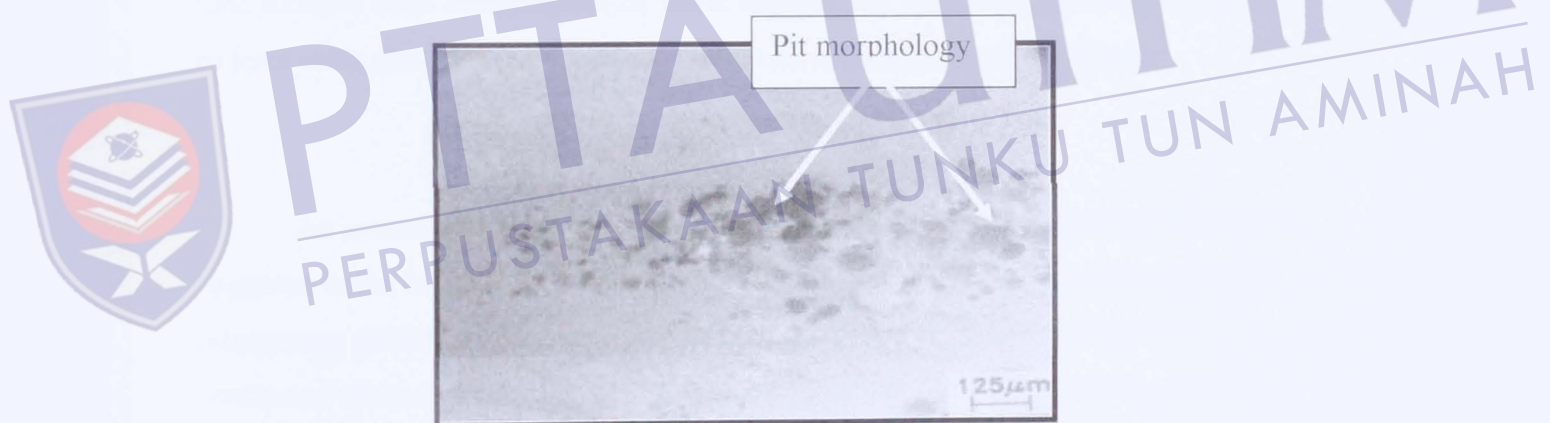
Corrosion has been classified in many different ways. One method divides corrosion into low temperature and high temperature corrosion. Another separates corrosion into direct combination (or oxidation) and electrochemical corrosion. The preferred classification here is Wet corrosion and Dry corrosion. Wet corrosion occurs when a liquid is present. This usually involves aqueous solution or electrolyte and accounts for the greatest amount of corrosion by far. Dry corrosion occurs in the absence of a liquid phase or above the dew point of the environment. Vapors and gasses are usually the corodents. Dry corrosion is most often associated with high temperature. An example is attack on steel by furnace gasses [21].

#### **2.5.1.1.1 Pitting Corrosion**

Pitting corrosion is form of extremely localized attack that results in holes in the metal (Figure 2.3). These holes maybe small or large in diameter, but in most

cases they are relatively small. Pits are sometimes isolated or so close together that they look like a rough surface. Generally a pit may be described as a cavity or hole with the surface diameter about the same as or less than the depth.

Pitting is one of the most destructive and insidious forms of corrosion. It causes equipment to fail because of the perforation with only a small percent weight loss of the entire structure. It is often difficult to detect pits because of their small size and because the pits are often covered with products. In addition, it is difficult to measure quantitatively and compare the extent of pitting because of the varying depths and numbers of pits that may occur under identical conditions. Pitting is also difficult to predict by laboratory test. Sometimes the pits require a long time—several months or a year—to show up in a localized and intense form of corrosion, and failures often occur with extreme suddenness [21].



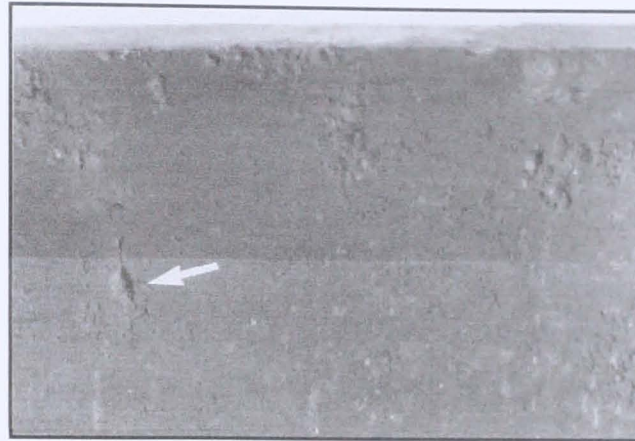
**Figure 2.3:** SEM micrographs showing pit morphology [22].

### 2.5.1.1.2 Oxygen Pitting

Oxygen pitting occurs with the presence of excessive oxygen in boiler water. It can occur during operation as a result of in-leakage of air at pumps, or failure in operation of preboiler water treatment equipment. This also may occur during extended out-of-service periods, such as outages and storage, if proper procedures are not followed in lay-up. Non-drainable locations of boiler circuits, such as superheater loops, sagging horizontal superheater and reheater tubes, and supply lines, are especially susceptible.

More generalized oxidation of tubes during idle periods is sometimes referred to as out-of-service corrosion. Wetted surfaces are subject to oxidation as the water reacts with the iron to form iron oxide. When corrosive ash is present, moisture on tube surfaces from condensation or water washing can react with elements in the ash to form acids that lead to a much more aggressive attack on metal surfaces.

An investigation was carried out by Heyes [23] on oxygen pitting failure of a baggasse boiler tube. This investigation the optic microscope and scanning electron microscopy (SEM) with an energy dispersive X-ray spectroscopy was used to conducted microstructural study of metals. He reported that the pitting observed in the tube was a result of oxygen pitting (Figure 2.4) and probably occurred during the wet storage period due to inadequate maintenance of the water levels, pH and the amount of oxygen scavenger.

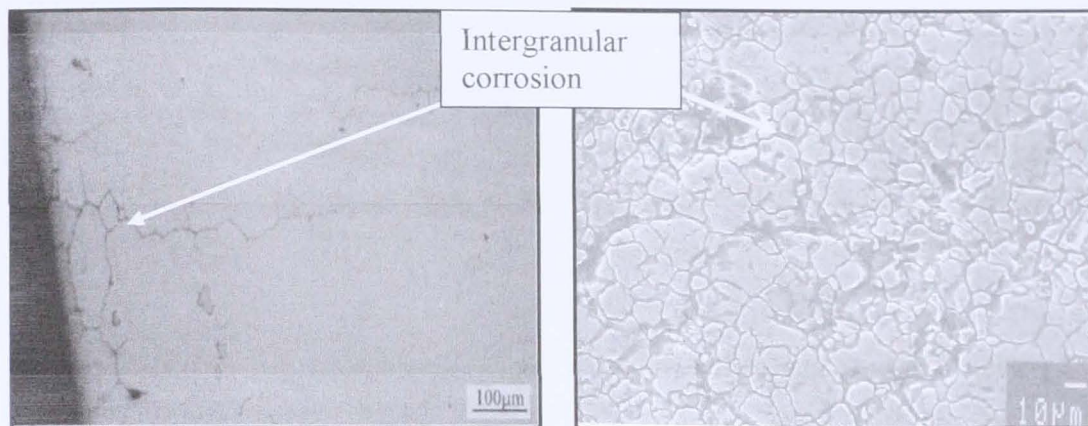


**Figure 2.4:** Close up view of crack (arrowed) and pitting at the point of minor leakage [23].

During wet storage the boiler should have been kept completely filled with water (to exclude air) or nitrogen copped, the pH maintained around 11 and the water dosed with sodium sulfite to a residual level of at least 100 ppm. The most likely cause of the cracking observed in the tube is vibrations caused by harmonic oscillation. Obviously, the vibrations must be minimized or eliminated, if possible.

#### 2.5.1.1.3 Intergranular Corrosion

Intergranular corrosion is one of the major localized corrosion problems faced by austenitic stainless steel components used in various industries including nuclear and thermal power, Chemical, petrochemical, pulp and paper, oil fertilizer and refineries [24]. Intergranular corrosion refers to the preferential corrosion attack along the grain boundaries in certain corrosive environments which results in the loss of engineering properties. Intergranular corrosion is illustrated in Figure 2.5. The grain boundary material, where is limited area, acts as an anode, and the large areas of grains act as cathodes. This results in the flow of energy from the small anode area to the large cathode area, which causes rapid attack penetrating deeply into the metal.



**Figure 2.5:** Intergranular corrosion crack and early intergranular corrosion fatigue [21, 25].

Intergranular corrosion can be caused by the improper heating of austenitic stainless steel. All austenitic stainless steels contain some amount of carbon. When the metal is heated to its sensitizing range  $454^{\circ}\text{C}$  to  $899^{\circ}\text{C}$  ( $850^{\circ}\text{F}$  to  $1650^{\circ}\text{F}$ ), as a welding, carbon is precipitated out at the grain boundaries in the form of chromium carbide. The composition has been changed by removing chromium from this area, thus making it susceptible to corrosive attack. If the stainless steel is annealed after it has been sensitized, this effect can be reduced. Annealing is accomplished by heating the alloy to  $982^{\circ}\text{C}$  ( $1800^{\circ}\text{F}$ ) or higher (depending on the specific alloy) and quickly cooling it through the sensitizing range to prevent the carbon from precipitating out [21].

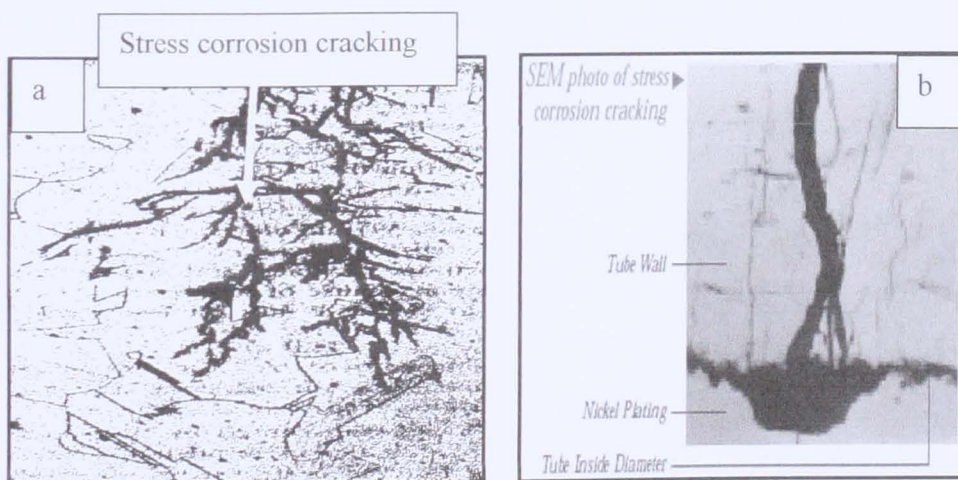
#### 2.5.1.1.4 Stress Corrosion Cracking (SCC)

Stress corrosion cracking is the result from the simultaneous action of residual or applied tensile stress and chemical action by a corrosive environment. Stress corrosion cracking manifests itself as a crack in the metal not necessarily accompanied by corrosion showing in Figure 2.6. This simultaneous influence of

corrosion and stress vastly differs from the mechanism of cracking of a metal exposed to any one of them. Time required for a initiation, nucleation and subsequence propagation of stress cracking that leads to the ultimate failed is dependent on various factor such as material composition, fabrication history, type of intensity of corrosive environment and magnitude of internal, residual or applied stress, Stress corrosion cracking frequently in both aluminum and magnesium alloys as well as in steels [26].

For stress corrosion cracking to take place all three conditions must be met simultaneously, the component needs to be in a particular crack promoting environment, the component must be made of a susceptible material, and there must be tensile stresses above some minimum threshold value. An extremely applied load is not required as the tensile stresses may be due to residual stresses in the material.

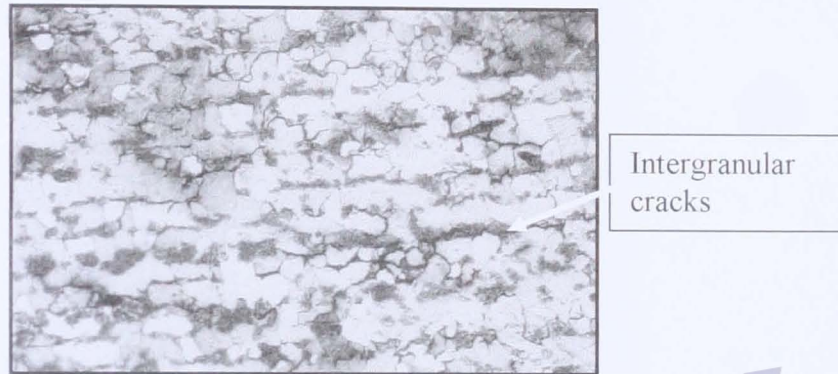
The stress corrosion cracking most commonly is associated with austenitic (stainless steel) superheater materials and can lead to either transgranular or intergranular crack propagation in the tube wall. It occurs where a combination of high-tensile stresses and a corrosive fluid are present, the damage results from cracks that propagate from the inside diameter Figure 2.6a and 2.6b. The source of corrosive fluid may be carryover into the superheater from the steam drum or from contamination during boiler acid cleaning if the superheater is not properly protected.



**Figure 2.6:** SEM micrograph of stress corrosion cracking [26, 27, 28].



Srikanth et al. [29] has done experimental investigation on phosphate induced stress corrosion cracking in water wall tube from a coal fired boiler. The failure of a water wall tube in a coal-fired boiler from a thermal power station was analyzed. In this investigation the microscope optic (MO), scanning electron microscopy (SEM) with an energy dispersive X-ray spectroscopy (EDS) and energy dispersive X-ray diffraction was used to study the microstructural of metals.



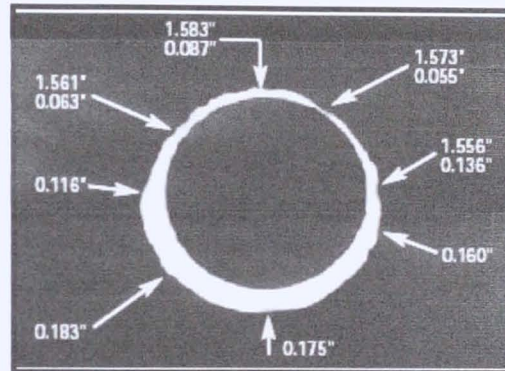
**Figure 2.7:** Microstructure of the cross section at the failed zone towards the waterside surface. The structure reveals ferrite + pearlite and intergranular cracks [29].

They reported that the failure in the water wall tube initiated locally at the waterside surface because of caustic corrosion. The corrosive environment appears to be related to the presence of excess amounts of sodium phosphates in the feed water. Figure 2.7 showed the subsequent failure of the tube has occurred by phosphate induced intergranular stress corrosion cracking.

#### 2.5.1.1.5 Fireside Ash Corrosion

Fireside ash corrosion is a function of the ash characteristics of the fuel and boiler design. It usually is associated with coal firing, but also can occur for certain types of oil firing. Ash characteristics are considered in the boiler design when

establishing the size, geometry and materials used in the boiler. Combustion gas and metal temperatures in the convection passes are important considerations. Damage occurs when certain coal ash constituents remain in a molten state on the superheater tube surfaces. Symptoms; External tube wall loss and increasing tube strain. Tubes commonly have a pock-marked appearance when scale and corrosion products are removed (see Figure 2.8).



**Figure 2.8:** Sectional photo of tube with severe wall loss from fireside ash corrosion [28].

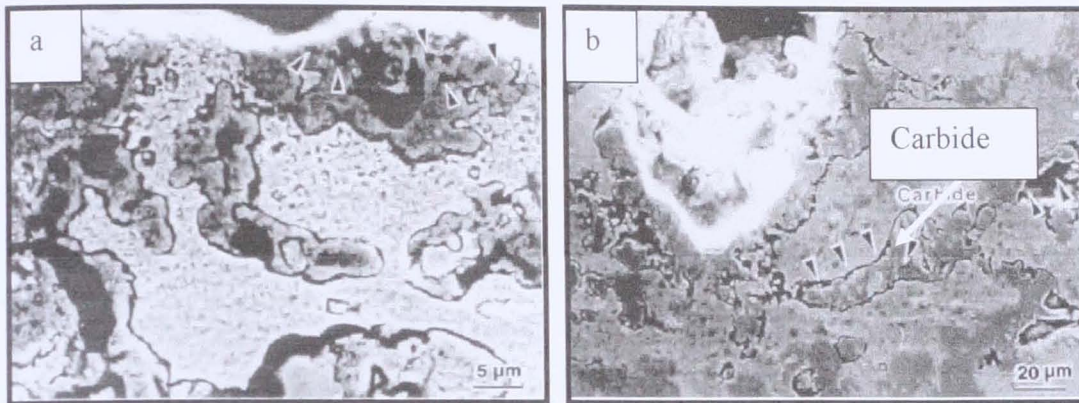
This molten ash can be highly corrosive. In coal fired boilers, the liquid phase is a mixture of sodium and potassium iron trisulfate ( $\text{Na}_3\text{Fe}(\text{SO}_4)_3$  and  $\text{K}_3\text{Fe}(\text{SO}_4)_3$ ) respectively. Mixtures of these melt at as low as  $555^\circ\text{C}$  ( $1030^\circ\text{F}$ ). In oil-fueled boilers, the liquid phase is a mixture of vanadium pentoxide ( $\text{V}_2\text{O}_5$ ) with either sodium oxide ( $\text{Na}_2\text{O}$ ) or sodium sulfate ( $\text{Na}_2\text{SO}_4$ ). Mixtures of these compounds have melting point  $540^\circ\text{C}$  ( $1000^\circ\text{F}$ ). Practically all the elements of chemical periodic table are present in coal. According to contents, the elements can be divided into three groups: major element (C, H, O, N, S); minor elements which include the coal mineral matter (Si, Al, Ca, Mg, K, Na, Fe, Mn, Ti) and halogens (F, Cl, Br) [30].

Analysis of failures in boiler tubes due to fireside corrosion in waste heat recovery boiler has been done by Srikanth et al. [31]. In their investigation the both of scanning electron microscopy with energy dispersive X-ray spectroscopy and energy dispersive X-ray diffraction was used to analyze the microstructural and chemical composition of oxide scale/deposits. They reported that the deposits in

superheater sections mainly the hematite and corundum solid solution whereas the deposits in the high pressure evaporator and economizer section are mainly hydrated iron sulfate and iron hydroxide sulfate.

They reported that the fireside corrosion of the superheater tubes, high pressure evaporator and economizer in the present case is gas phase with the metal surfaces. It can also be deduced that the fireside corrosion propensity in the superheater coils is likely to be mild (because of formation of  $\text{Fe}_2\text{O}_3$ ); corrosion propensity of high pressure evaporator and economizer is likely to be severe (because formation of hydrated iron sulfates).

An investigation was carried out by Anwar et al. [32] on failure analysis of furnace radiant tubes exposed to excessive temperature. In their investigation, the microstructural features were characterized using scanning electron microscopy (SEM). Energy dispersive X-ray spectroscopy (EDS) combined with SEM was used to determine the chemical composition. They reported that most evidence pointed out that the cause of failure was due to exposure to an excessively high temperature likely during decoking. Exposure to an excessively high temperature could have two detrimental effects. First, the creep rate was accelerated leading to the formation of grain boundary voids as observed (Figure 2.9). Service experience indicated that the life of a radiant furnace tube made of cast HK 40 stainless steel was reduced by as much as 90% when the service temperature was raised by only  $56^\circ\text{C}$  above the prescribed temperature. Creep deformation can lead to cracking of the protective oxide scale causing an accelerated carburization attack. Secondly, a higher temperature accelerated the rate of carburization attack as pointed out earlier.



**Figure 2.9:** (a) SEM image of failed tube illustrating voids in the surface oxide scale indicated by the arrows and (b) SEM image of failed tube at the sagged region illustrating large density of voids at grain boundaries [32].

However, it is very likely that the effect of creep was compounded by presence of a continuous network of grain boundary carbide due to carburization. Rapid cooling from a temperature near the melting point maintains a high concentration of C in super-saturation. To promote creep strength, the carbides must be in the form of fine dispersion in the austenite matrix which can be achieved by exposure to a relatively low temperature. However, as the temperature is increased, the carbides become coarser and lose their effectiveness as a source of strength. In contrast, slow cooling from the high temperature range promotes grain boundary precipitation of carbides. Further precipitation of grain boundary carbides occurs during subsequent exposure to elevated temperatures. Continuous networks of grain boundary carbides, however, are undesirable because they embrittle the alloy and promote intergranular cracking.

### 2.5.1.2 Failure Caused by Corrosion Fatigue and Mechanical Fatigue

Corrosion in general has the overall effect of reducing the strength of a structure, and if not detected, could progress to a state that eliminates the probably of

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