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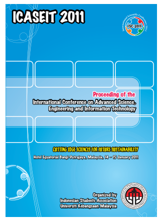

Failure analysis of high temperature superheater tube (HTS) of a pulverized coal-fired power station

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Abstract- **This paper presents the failure investigation of high temperature superheater (HTS) tubes. Samples were collected from one of the coal fired power plants in Malaysia, namely, Stesen Janakuasa Sultan Azlan Shah, Manjung (Manjung Power Station). After eight years of non-continuous services of three boilers, welded support-clips were completely separated (detached) from (HTS) tubes, which caused the wall thinning. Collected failed samples were undergone several experimental investigations including visual inspection, thickness measurement, Vickers hardness testing, and microstructure evaluation. The results revealed that some cracks were initiated at the heat-affected zone (HAZ) and propagated partly throughout the weld metal. The estimation on operating temperature and operating hoop stress show indication that the specimen may experienced a hig operating temperature. Other findings confirmed that the detachment of welded support-clips from HTS tubes may also caused by dissimilar metal weld (DMW) failure due to the differences in expansion properties of parent metal and weld metal.**

Keywords- **High temperature superheater (HTS) tube, coal-fired boiler, localized overheating, visual inspection, microstructure evaluation.**

I. Introduction

Boiler or steam generator plays a vital role in power plant for electricity generations. In a high capacity power plant, coal fired boiler is normally chosen in the purpose to increase the capacity of electricity generation, and prevents corrosion and reduces steam consumption of the steam turbine. In a coal fired steam generator, rows of tubes are heated by fireball with temperature of 530-1000˚C. Exposure of tubes to temperatures at the outer surface, high pressure inside the tubes, and flame contaminated with corrosive residues for a long period of time usually causes tube failures [1-3].

A pulverized coal-fired boiler is an industrial or utility boiler that generates thermal energy by burning pulverized coal also known as powdered coal or coal dust. This type of boiler dominates the electric power industry, providing steam to drive large turbines. Pulverized coal provides the thermal energy which produces about 50% of the world's electric supply. Superheater tubes are usually located in the hottest zone of a steam generator. The steam with highest pressure and highest temperature is carried inside the superheater tubes, which are exposed to very high temperature generated by combustion of coal. Therefore, the superheater tubes are most susceptible to high-temperature creep and corrosion failures [4-6]. Although the materials of superheater tubes are superior compared to other tubes, failures of superheater tubes occur most frequently. To prevent tube failures, which causes temporary shutdown of the power plant, assessment of the tubes are always conducted according to power plant preventive maintenance practices [7-8].

Boiler tube failures are leading cause of forced outages in fossil-fired boilers. It is extremely important to determine and correct the root cause to get the boiler back in operation and eliminate or reduce future outages. In order to evaluate the failure, all aspects of boiler operations leading to the failure should be investigated to fully understand the cause. There are many types of boiler tube failures, i.e, caustic attack, hydrogen damage, oxygen pitting, acid attack, stress corrosion cracking, water corrosion fatigue, superheater fireside ash corrosion, fireside corrosion fatigue, short-term overheat, long-term overheat, dissimilar metal weld (DMW) failure, erosion, and mechanical fatigue [9].

II. Brief Description of Boiler

The Manjung Power Station boilers are of sub-critical pressure, single reheat and controlled circulation type. Each boiler is fired with pulverized coal to produce steam for the continuous electricity generation of 700 MW. The boilers are designed to fire coals within the bituminous rank. The combustion circuit consists of a single furnace, with direct tangential firing and balanced draught. Light fuel oil burners are available for boiler start-up and for coal ignition or combustion stabilization. The maximum heat input that can be achieved when firing fuel oil is 40% of the boiler maximum continuous rate (BMCR). The boiler has been designed to comply with the Malaysian environment requirements, i.e, NOx control is achieved with a low NOx combustion burner system including over fire air (OFA) ports. An electrostatic precipitator (ESP) removes dust in the flue gas at the boiler outlet and a flue gas desulphurization (FGD) plant, scrubs the flue gas and controls the SO_2 emission level at the stack.

The firing equipment consists of four elevations, 16 remote controlled fuel oil burners equipped with high-energy igniters, used to start-up the boiler and to support combustion of the pulverized coal at low firing rates. The capacity of oil burners is 40% of the BMCR. Seven elevations, 28 coal burners located just above or below a fuel oil burner, the capacity of coal burners is 100% of BMCR when firing coal within the designed range. All the burners are located at the furnace corners (tangential firing).

The major auxiliary equipment consists of three boiler circulating pumps, two force draft fans, two primary air fans and two induced draft fans. All these fans are centrifugal fans with control vanes at the inlet to adjust the flow or the pressure. There are also two steam air preheaters, one soot blowing equipment, two electrostatic precipitators, and one coal milling plant consists of seven vertical bowl mills, type BCP2820, and one wet flue gas desulfurization plant (FGD). The key data of Manjung Power Station are shows in Table 1.

TABLE 1.
SUMMARY OF OPERATING CONDITIONS OF MANJUNG POWER STATION [15]

Output (MW)	3 X 700
Number of boilers	3
Live Steam Flow (t/h)	2,390
Live Steam Pressure (bar abs)	175
Live Steam Temperature (˚C)	540
Feed water Temperature (˚C)	277
Fuel	Coal
Ignition fuel	Light oil
FGD performance (%)	96% SO_2 removal
Generator Type	GIGATOP
Generator rating (MVA)	043
Power factor	0.85
Terminal voltage (kV)	23
Frequency (Hz)	50
Short-circuit ration	0.51
Generator efficiency (%)	98.9
Excitation system	Static
Generator Cooling System	Hydrogen + water

III. Boiler Tube Descriptions and Operation History

The boiler tubes used by Manjung Power Station are classified as high temperature superheater (HTS) tubes. Table 2 shows the details and operating conditions of high temperature superheater tube. The material used for this HTS tube is A213-T91 which is similar to modified 9Cr-1Mo steel. For the tube thickness, the allowance range is -0% to +33% depends on the location of tubes in the boiler. The minimum thickness requirement of tubes is 3.85 mm, which is a standard dimension set by Alstorm, manufacturer of Manjung Power Station Boiler, for normal operation of the boiler. According to the design specification, the high temperature superheater tube will be considered fail if the tube thicknesses are below acceptable limit, which is 3.85 mm.

TABLE 2
MATERIAL SPECIFICATIONS, DIMENSION OF HTS TUBES AND OPERATING CONDITION

Material	SA-213MT91 (ASME P-Number 5B)
Diameter, Ø	38.0mm
Thickness, t	4.57mm
Superheated steam flow	2390 t/h
Superheated steam pressure	182 bar
Superheated steam temperature	543˚C

Major overhaul of Manjung Power Station's boiler unit 3 was conducted from October 17th, 2008 till December 5th, 2008. From the previous overhaul, it is estimated that the boiler have run for 27,000 hours which is equivalent to 3 years. During the inspection at boiler nose area (Level 68 m), some tubes were found damaged due to the detachment of either clips, supports or/and brackets on HTS tubes. Assessment on damaged tubes was carried out to determine the severity in terms of the remaining of the wall thickness.

IV. Brief Description of SA213-T91

This enhanced ferritic steels of grade 91 and grade 92 is meant to overcome the restriction of where ferritic steels of grade 21 and grade 22 are lacking off. The requirement for CO_2 reduction and high efficiency power plant require a steam cycle to be operated as high as 600°C[10]. T91 offers a good creep-strength compared that allowed it to be operated at higher temperature. Correlation between the hardness (HV) and Larsen Miller parameter for T91 is express as [11]

$$Hardness\ (HV) = 933 - 0.01825\,P \tag{1}$$

where P, is the Larsen Miller parameter and defined as

$$P = \left(\frac{9}{5}T_c + 492\right)(C + \lg t) \tag{2}$$

Which, T_c is operating temperature in Celsius, C is constant of 20 and t is rupture time in hours. Both equation 1 and 2 are used to estimate the operating temperature with the given hardness value and operating hours. From the estimated operating temperature of the received tube, comparison to operating temperature is made. The hoop stress of the tube is given by

$$\sigma_h = P\,\frac{(r + \frac{h}{2})}{h} \tag{3}$$

where P is the steam pressure, r and h is inner radius and wall thickness respectively.

V. EXPERIMENTATIONS AND RESULTS

Four samples of failed HTS tubes from coal fired boiler unit 3 were collected. The as-received failed HST tubes are shown in Fig. 1. Visual inspection, dimensional measurement, non-destructive testing, hardness measurement, and microstructure evaluation were conducted to analyze the failure of the collected high temperature superheater (HTS) tubes.

Fig. 1 The as-received failed high temperature superheater (HTS) tubes

Visual inspection revealed that all examined HTS tubes were found to be suffered from thinning problem located where the surfaces are welded to clips, supports or brackets as shown in Fig. 2. Ferritic material has completely separated leaving the weld zone and parts of the parent metal of HTS are detached together with the welded metal. The evidence of corrosion pitting is found in a distinct band on the outer surface of the tube (Fig. 3). Corrosion deposits are present throughout the pit defects, with most of the pits having an oxide crust. The tube corrosion pitting is likely a result of oxygen corrosion, resulting from oxygenated water in contact with the tube surfaces.

Fig. 2 Close view of failed HTS tubes

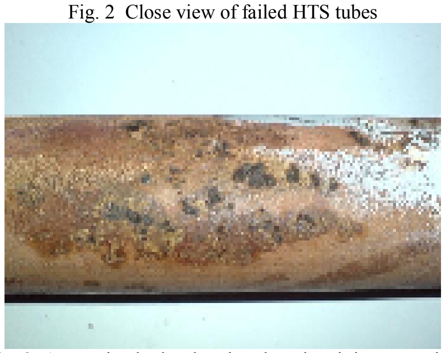

Fig. 3 As-received tube showing the tube pitting corrosion

Diameter was measured by Vernier Caliper at four different locations along the failed tube in order to measure the thickness of the failed tube. The differences of the measured diameter and the original diameter were calculated (Table 3). The increment of the diameter is mainly due to the ash slagging on the outer surface, deposition and scale formation. Ultrasonic thickness test measurement (UTTM) was also conducted to get the exact wall thickness of the failed zone of tubes.

However, the results of liquid penetration testing did not indicate the occurrence of any crack across the external surface of welded location (Fig. 4). Measurement of the remaining wall thickness on the damaged zone of the tube was conducted on tube no 1 and tube no 2 through ultrasonic thickness test measurement (UTTM). The measurements of wall thickness of the tube surrounding the damaged zone from three different locations along the tube were also conducted. The minimum remaining wall thickness at the damaged zone of HTS tubes and wall thickness at non-damaged zone along the HTS tubes are shown in Table 4 and Table 5, respectively.

TABLE 3
DIAMETER MEASUREMENT OF FAILED HTS TUBES

Tube No	Diameter (mm) Point				
	1	2	3	4	Average
1	38.55	38.80	38.55	38.60	38.63
2	38.60	38.55	38.50	38.50	38.54
3	38.50	38.65	38.45	38.60	38.55
4	38.45	38.75	38.70	38.70	38.65

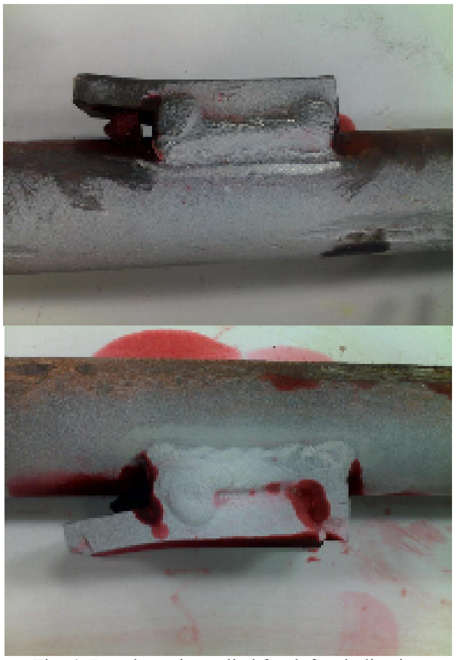

Fig. 4 Developer is applied for defect indication

TABLE 4
MINIMUM REMAINING WALL THICKNESS MEASUREMENTS AT DAMAGED ZONE

Measurements	Remaining wall thickness (mm)	
	tube 1	tube 2
1	3.72	3.74
2	3.68	3.66
3	3.62	3.67
Average	3.67	3.69

Hardness measurement was conducted across the weld metal, heat affected zones (HAZ) and base metal of HTS tubes. Heat affected zone (HAZ) was located adjacent to weld metal zone, which composed of parent metal that did not melt but was heated to a high temperature for a sufficient period promoted to the grain growth. As a consequence, the mechanical properties and microstructure of HAZ have been altered by the heat of welding. The results of hardness measurement are shown in Table 6.

TABLE 5
WALL THICKNESS MEASUREMENTS AT NON-DAMAGED ZONE

Measurements	Wall thickness (mm)	
	Tube No 1	Tube No 2
1	5.40	5.37
2	5.13	5.25
3	5.23	5.22
Average	5.25	5.28

TABLE 6
HARDNESS MEASUREMENT READINGS (VICKERS) ACROSS THE PARENT METAL, HEAT AFFECTED ZONE AND WELD METAL

Locations	Measurements				Average
	1	2	3	4	
Base metal	248	252	246	250	249
HAZ	213	222	215	220	217.5
Weld metal	245	250	248	251	248.5

Referring to the table 6, the estimated operating temperature of the received tube is tabulated at table 7, estimated using both equations 1 and 2.

TABLE 7
ESTIMATED OPERATING TEMPERATURE

Locations	Hardness, HV	Operating Temperature ^{o}C
Base metal	249	580
HAZ	217.5	620
Weld metal	248.5	580

Referring to the estimated temperature at table 6, we can observe that all sample tube as received, experienced an operating temperature above the design temperature as shown in table 1 and table 2. Heat affected zone (HAZ) was estimated way above 600^{o}C for which ferritic steels are reported to start to decarburize.

Using equation 3, the hoop stress σ_h, is estimated at 88.69MPa at temperature of 620^{o}C. Comparing to the maximum allowable stress of T91, the estimated value for the operating hoop stress is found to be excessive as shown in table 8.

TABLE 8
THE MAXIMUM ALLOWABLE STRESS OF T91 FOR DIFFERENT TEMPERATURE [12]

Temperature ^{o}C	566	593	621	649
Max. allowable stress MPa	88.95	71.02	48.27	29.65

Sample from tube no 4 was prepared and subjected to microscopic examination. Fine cracks are observed on the weld metal surface located adjacent to the heat affected zone (Fig. 5). General view of the fracture morphology on the weld metal of the failed HTS tube was brittle. However, the observed fine cracks were originated from the high stressed HAZ and propagated partly throughout the weld metal (Fig. 6). It is suspected that the cracks were grown during the operations of the tube, particularly the action of shutdown and start-up assisted the crack propagation. In order to establish the crack path and confirm the finding that the HTS tube are failed as a result of dissimilar metal weld (DMW) failure, detailed metallographic examinations have been conducted. Fig. 7 shows that the failure tends to be catastrophic where the tube was failed across the heat affected zone of the weld section of HTS tube.

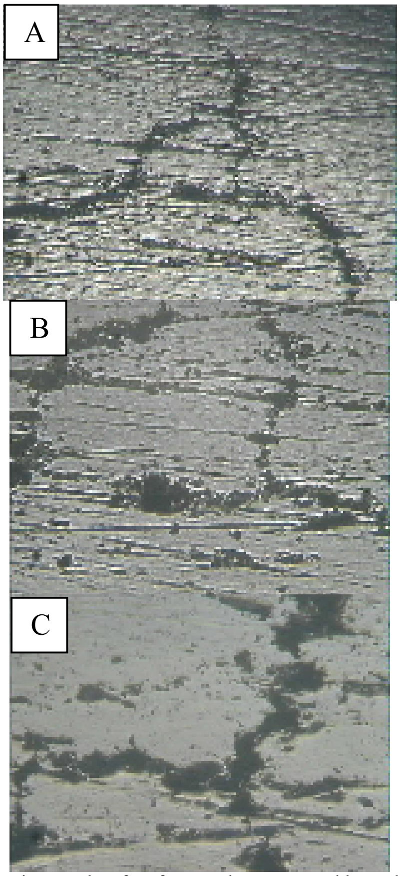

Fig. 5 Photomicrographs of surface crack zone on weld metal: (A) 4 x 0.1 zoom, (B) 10 x 0.25 zoom, (C) 20 x 0.4 zoom

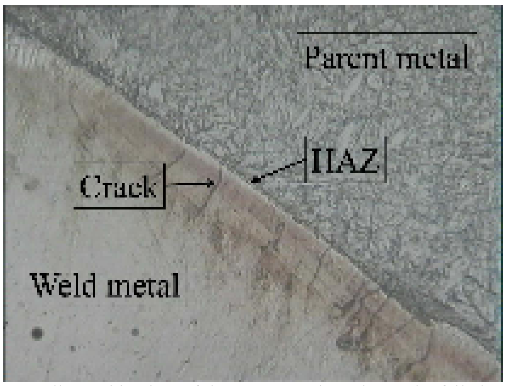

Fig. 6 Metallographic view of the propagated cracks on the failed zone on HTS tube (20 x.04 Zoom)

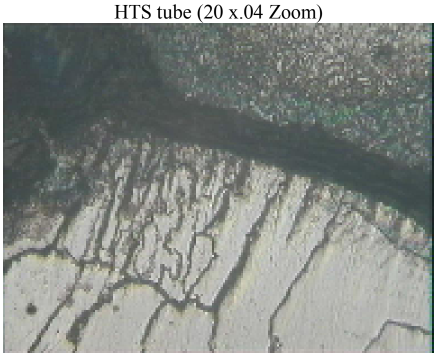

Fig. 7 Photomicrograph showing DMW creep voids at ferritic interface

VI. Discussions

The welding joints between the tube and clip (Fig. 8) are original welding by the boiler manufacturer in order to hold these tubes in certain position. During the outage inspection, the tube was found detached from clips, supports or/and brackets and the surface of the tube was detached together with the welded metal. These caused the reduction of thickness at the welded location of the tubes.

Fig. 8 General view of welding between superheater tube and support-clip

The detachment of the welded clip from the superheater tube might be caused by the brittle cracking in the heat-affected zone (HAZ) of the weld [13]. As the temperature of the fire-side surface of the tube decreased, the condensation of escaping steam became more. The high sulfur coal burning products are deposited on the outer surface of the tubes and as a consequence, pitting corrosion occurred [14-17]. This might be occurred during the extended out-of-service periods such as outages of boiler.

Wetted surfaces are subjected 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 a much more aggressive attack on metal surfaces. Diameter measurements and liquid penetration testing did not show any evidence of creep damage. The average remaining wall thickness across the location that suffered thinning problem on tube no 1 and tube no 2 are 3.67 mm and 3.69 mm, respectively, which were below the minimum requirement, i.e., 3.85 mm. In this case, these

HTS tubes ware considered failed and required to be replaced with new tubes due to the safety purposes.

The results of the hardness measurement indicated that the hardness values of the weld metal and parent metal for HTS tube were higher than that of heat affected zone (HAZ). This of course assisted in the initiation of crack growth within the parent metal and weld metal due to the low toughness and strength. Dissimilar metal weld (DMW) failures are attributed to several factors, such as high stresses at the austenitic to ferritic interface due to differences in expansion properties of the two different metals, excessive external loading or thermal cycling, and creep of the ferritic material [7]. Therefore, DMW failures are a function of the boiler operating temperatures. During the boiler outages, the fast cooling from the high temperature leads to contraction or expansion that may resulted in initiation of cracks.

VII. CONCLUSIONS

Failure analysis of the failed high temperature superheter (HTS) tube of a pulverized coal fired power station was conducted through visual inspections, thickness measurement, and metallurgical examinations. It was found that the failure of HTS tubes was caused by dissimilar metal weld (DMW) where the thermal properties of parent metal and weld metal are different. The root cause might be the non-continuous operation of the boiler where the materials were expanded during the operation and contracted back during the outage period.

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