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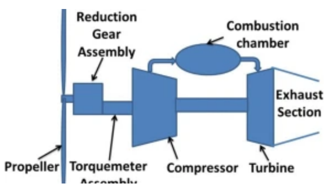

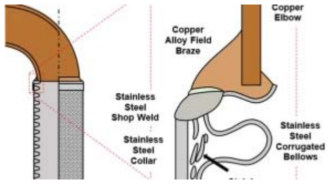
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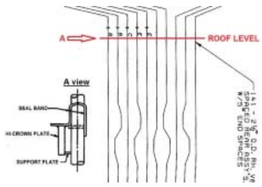
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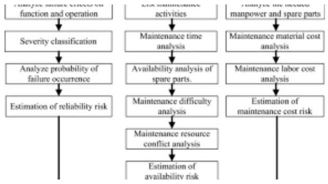

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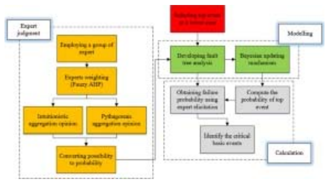

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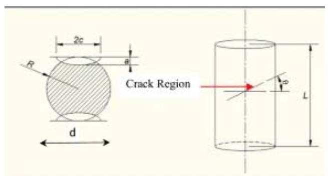

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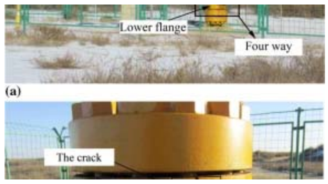
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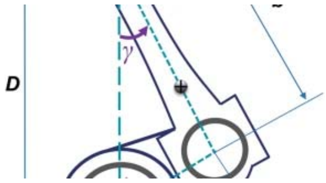
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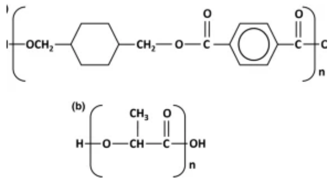


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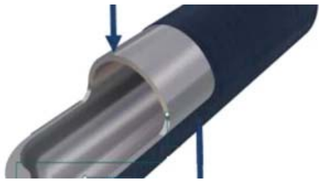

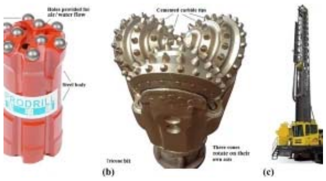
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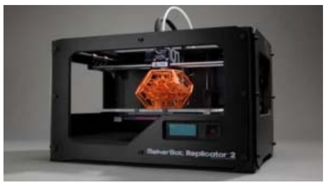

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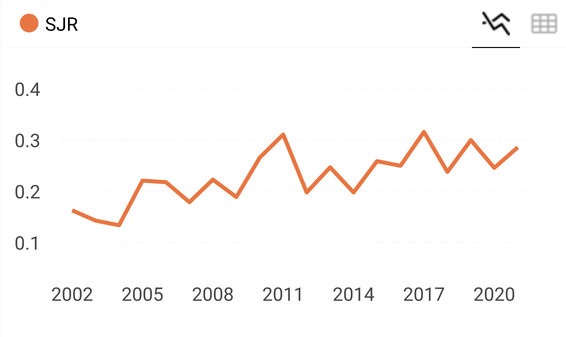

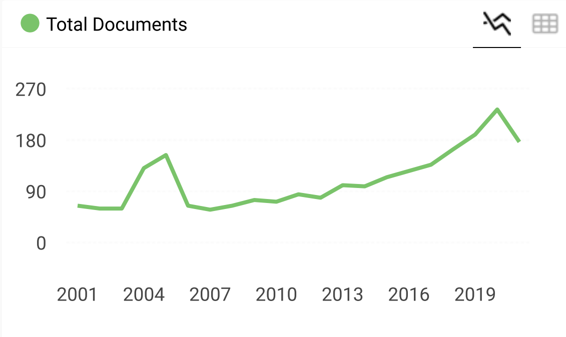

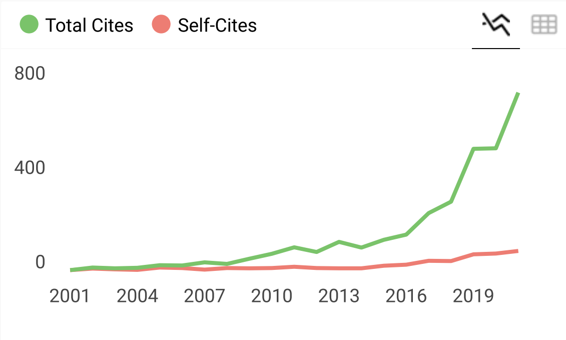

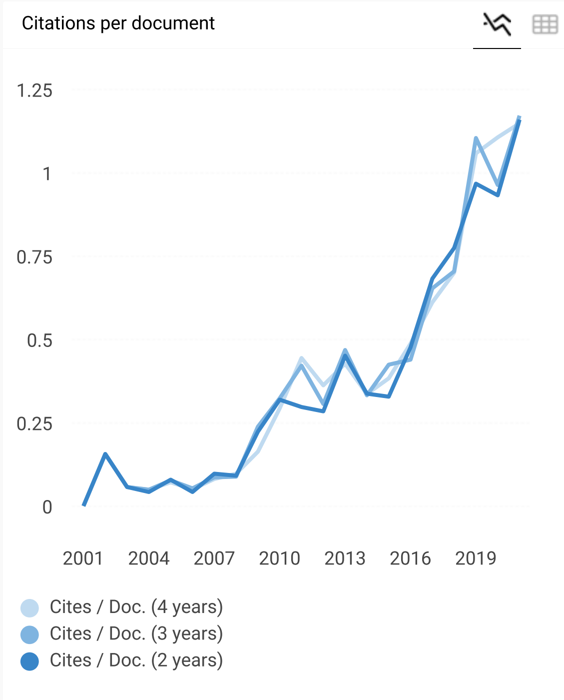

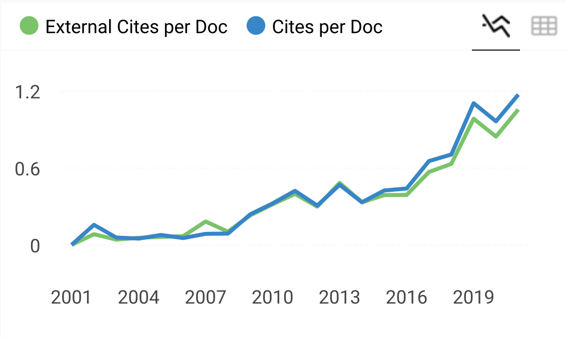

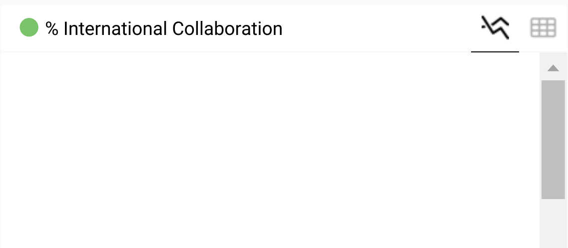

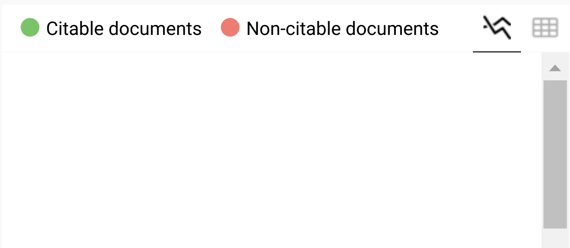

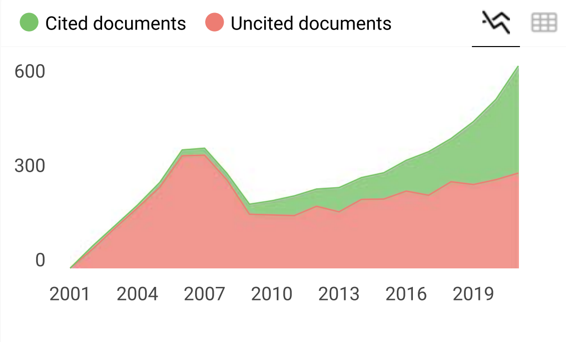

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Failure Analysis of Secondary Superheater Tube in a 600-MW Coal Power Plant

M. Nurbanasari, H. Abdurrachim & M. M. Prihadi

Journal of Failure Analysis and Prevention **19**, 453–460 (2019)

Abstract

A failure analysis was carried out on an A213 T91 secondary superheater tube after 4 months of overhaul. The failure caused the 600-MW coal power plant was shut down. The investigation consisted of visual inspections, microstructure analysis, Vickers hardness test, x-ray diffraction, and ash fusion temperature test and ash content analysis. The failed tube had a thin-lip rupture with sharp edges and experienced a decrease in hardness in the area of lip rupture. The microstructure analysis shows the coarse carbide and some isolated voids. Corrosion products were detected in slag deposits, and nonuniform thin oxide layer in the inner wall of the tube was observed. It is concluded that the main failure of the failed tube was due to the formation of slag deposits on the

outer surface of the tube wall. This formation has resulted in simultaneously occurring phenomena, which was the localized flue gas erosion followed by the rapid overheating of the tube. The formation of slag deposits was in consequence of the use of coal with lower ash fusion temperature than required coal ash fusion temperature for the power plant.

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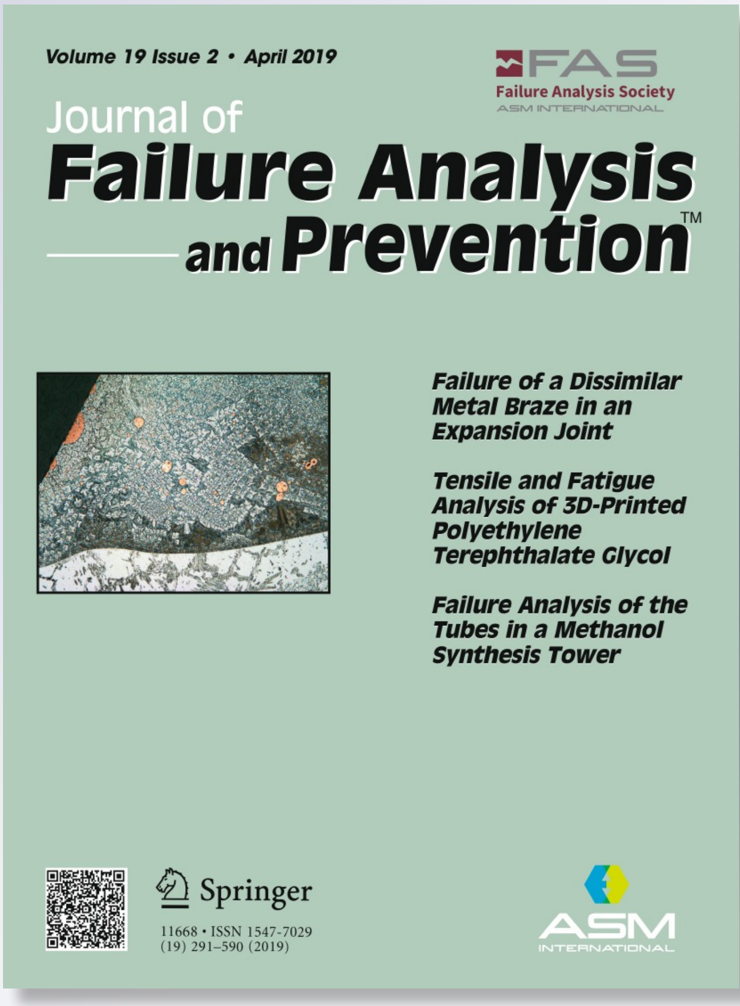

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TECHNICAL ARTICLE—PEER-REVIEWED

Failure Analysis of Secondary Superheater Tube in a 600-MW Coal Power Plant

M. Nurbanasari · H. Abdurrachim · M. M. Prihadi

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Abstract A failure analysis was carried out on an A213 T91 secondary superheater tube after 4 months of overhaul. The failure caused the 600-MW coal power plant was shut down. The investigation consisted of visual inspections, microstructure analysis, Vickers hardness test, x-ray diffraction, and ash fusion temperature test and ash content analysis. The failed tube had a thin-lip rupture with sharp edges and experienced a decrease in hardness in the area of lip rupture. The microstructure analysis shows the coarse carbide and some isolated voids. Corrosion products were detected in slag deposits, and nonuniform thin oxide layer in the inner wall of the tube was observed. It is concluded that the main failure of the failed tube was due to the formation of slag deposits on the outer surface of the tube wall. This formation has resulted in simultaneously occurring phenomena, which was the localized flue gas erosion followed by the rapid overheating of the tube. The formation of slag deposits was in consequence of the use of coal with lower ash fusion temperature than required coal ash fusion temperature for the power plant.

Keywords Superheater tube · Flue gas · Overheating · Erosion

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Introduction

A boiler plays a vital element in coal-fired power plants. It consists of important components to maintain the power supply such as boiler tubes, superheater, economizer and air heater. One of the crucial components of pressure parts is the superheater tube that is basically a heat exchanger in which heat is transferred from furnace gas to steam. The superheater tubes experience high pressure and are located in the radiation zone of boiler. The temperature of flue gas (hot gas) in this zone is around 700 °C, and the temperature of steam coming out of the superheater tubes is around 540 °C [1]. Although the tubes usually are used for 20 years and some have been in use for much longer, tube failure often occurs. Improper heat transfer between steam and furnace gas in the superheater tube creates serious problems, which leads to shut down the whole power plant. It has been reported that creep damage [1–4], fatigue [5, 6], excessive thermal stresses, water/steam corrosion [7], short-term overheating [8] are general mode failures of superheater tubes. This paper reports a failure analysis on secondary superheater tubes in a 600-MW coal power plant that has operated for 22 years to prevent the same failures in the future. The power plant was shut down after operating for 4 months since overhaul maintenance in December 2017. It seems that during overhaul maintenance, the cleaning process was done poorly as the tubes were covered with thick slag deposits (see Fig. 1). The power plant was designed for coal with ash fusion temperature of 1300 °C. The design temperature and the operating pressure of the tube were 540 °C and 17 MPa, respectively. The original outside diameter of the failed tube was 60.3 mm, and wall thickness was 8.0 mm. The leaked tubes were removed and then replaced. One piece of failed tube was received for conducting the investigation.

Methodology

Failure analysis was performed on the failed (leaked) tube. The investigated tube is shown in Fig. 2, and visual inspection was carried out around the lip rupture. For detailed analysis, the failed tube was cut along the cross section and some microstructure/hardness samples were collected from different locations (numbers 1, 2 and 3 in Fig. 2).

The metallographic samples were prepared by using standard metallographic techniques, and the samples were etched with 3% nital solution to reveal the microstructures.

Fig. 1 Secondary superheater tubes in installed condition taken from the manhole

Fig. 2 Cross section of the failed tube (the numbers indicate the location of samples)

The microstructure was analyzed by optical and scanning electron microscope (SEM) equipped with an energy-dispersive x-ray (EDX) analysis facility. Average hardness data were taken from six times measurement on the microstructure samples conducted on Vickers hardness tester with a 500 g load and dwelling time of 15 s. X-ray diffraction was also conducted to identify the slag deposits of fly ash on the outer wall of the tube. The International Centre for Diffraction Data (ICDD) database from 2002 was applied to identify the phases present. In addition, the samples for chemical composition and microstructure analysis for material verification of the failed tube were taken 500 mm away from the lip rupture. The bulk chemical composition of slag was analyzed by optical emission spectrometer, and the wall thickness was measured by a micrometer. Ash fusion temperature test and coal fly ash analysis of the slag deposits were also performed to evaluate the melting and slagging behavior using the standard method of ASTM D1857-2017 and ASTM D3682-2013, respectively.

Results and Discussion

Material Verification of the Failed Tube

The optical emission spectrometer result shows that the chemical composition of the failed tube consists of 0.12% C, 0.48% Mn, 8.89% Cr, 1% Mo, 0.39% Si, 0.2% V, 0.02% P, 0.004% S (in wt.%) and the remainder is iron. Microstructure analysis in Fig. 3 (the location of sample number 3 in Fig. 2) exhibits that the failed tube had carbides along the grain boundaries with ferrite matrix and the average hardness is 196 HV.

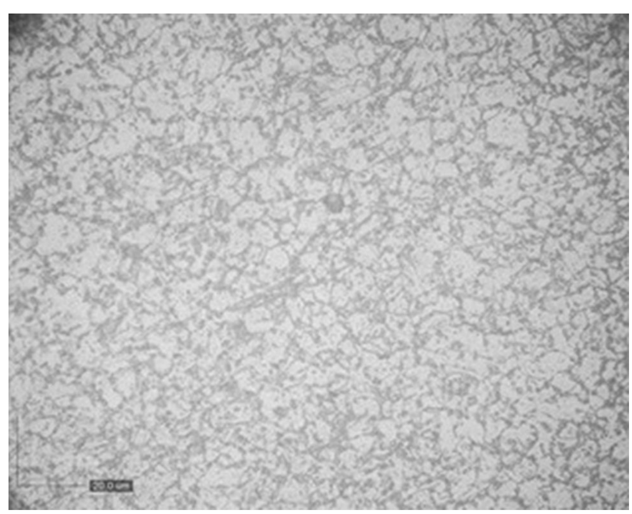

Fig. 3 An optical image of microstructure taken 500 mm away from the thin-lip rupture

Based on the aforementioned data, it can be concluded that the steel of the failed tube is in good agreement with the standard of ASTM A213 T91. The steel has been used widely for power plant application and has very good creep strength and good resistance to oxidation [9, 10]. Hence, failure owing to faulty chemistry of the steel is ignored.

Failure Analysis of Failed Tube

Visual Inspection

Visual inspection on the failed secondary superheater tube in Fig. 4a exhibits that the tube had a sharp edges and thin-lip rupture in the dimension around of 35 mm length and 36 mm width. The wall thickness measurement on the edge rupture shows the thickness reduction did not occur uniformly and the wall thickness was in the range 0.90–2.89 mm or 65–88% of the original wall thickness. The color around the lip rupture was light brown pertaining to superficial iron oxides. There is a change in color because during the operation the tube interacted with an extreme environment where steam flowed inside of the tube and the outside of the tube was exposed to flue gas (hot gas). No material loss was observed at the inner surface of the tube in Fig. 4b, which indicated that the thinning of the failed tube took place at outer surface. Visual inspection also reveals that the tube was bent or exhibited a bowed shape as shown in Fig. 5.

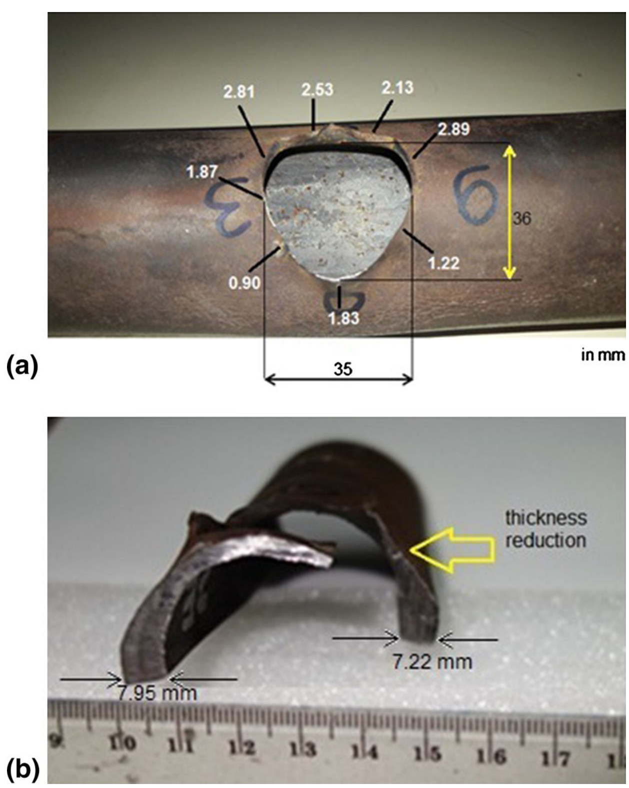

Fig. 4 (**a**) Failed tube suffered a thin-lip rupture (white numbers indicate the thickness). (**b**) Cross-sectional cutting of the failed tube shows that reduction in wall thickness started from the outer wall

Microscopic Examinations

A SEM micrograph of inner surface of the tube wall in the opposite side of the lip rupture is shown in Fig. 6. As can be seen, the tube had adherent nonuniform oxide scale layer with the thickness ranging from 0.223 to 0.272 mm that formed during the long-term operation. As the oxide layer is very thin, it will not block the flow of steam; hence, it is believed that the tube failure occurred due to factors outside of the tube wall.

A SEM image in Fig. 7a (the location of sample number 3 in Fig. 2) shows dispersed carbides and the presence of some isolated voids, which indicate creep damage. Furthermore, the microstructure on the lip rupture in Fig. 7b (the location of sample number 2 in Fig. 2) reveals that the long-term service in high temperature caused the carbide appearance to become spherical particles in a ferrite matrix and the void had been interconnected and formed a crack. The presence of some isolated voids and coarse carbides is related to overheating [1, 11] and creep damage. In addition, ductile fracture was also observed in the failed zone as seen in Fig. 7c (the location of sample number 1 in Fig. 2), which strengthens the evidence that the material had experienced softening and overheating.

To support the data, SEM-EDS analysis was carried out on the outer surface of the tube wall near the lip rupture. The result of SEM EDS in Fig. 8a shows the EDS spectra of inorganic elements, i.e., Si, Ca, Al, Fe, Ti and V, which contributed to the formation of slag deposits [12]. The presence of those inorganic elements is also supported by fly ash content analysis which evidences the content of TiO_2 as 0.58%, Al_2O_3 as 15.43% and Fe_2O_3 as 12.64%. Fly ash content analysis also detected the presence of Na_2O with the amount of 1.84%. It could be determined that those elements came from the fuel and coal being used in the combustion [13], which might relate to poor and incomplete fuel combustion conditions. It must be noted that the existence of certain inorganic elements in coal such as Si, Ti, V and Na would decrease the ash fusion temperature. SEM-EDS quantitative data of Fig. 8a in Table 1 show the

Fig. 5 Failed tube experienced plastic deformation (bowed shaped)

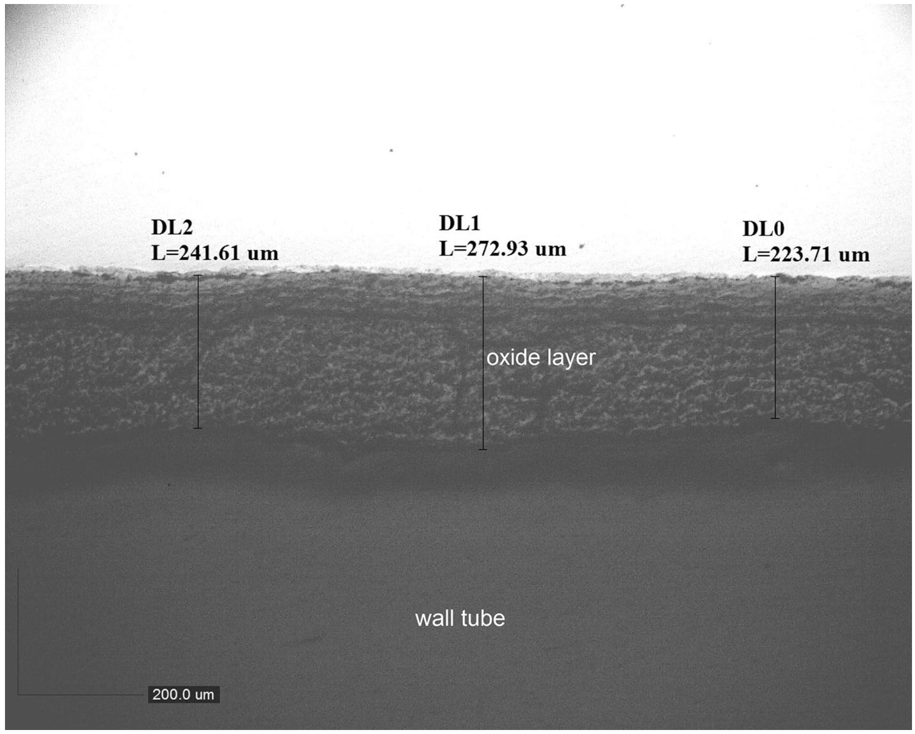

Fig. 6 Thickness of the thin adherent oxide scale layer at the inner surface in the opposite side of the lip rupture

presence of corrosive elements (Si and Ca) is below 20% mass (see Table 1) which suggested that the corrosion attack had occurred and was caused by the fusion of ash particles [14]. The spectrum of vanadium was also detected by SEM-EDS analysis as shown in Fig. 8b. The presence of vanadium with the amount of 0.75% mass (see Table 2) caused corrosion due to the formation of V_2O_5 which has a melting point of 690 °C [15, 16].

X-ray Diffraction Study

Slag deposits identification taken from outer wall of the tube was conducted using x-ray diffraction, and the results are presented in Fig. 9. The results obtained from XRD in Fig. 9 identified that deposits consist of alkali sulfate compound ($CaSO_4$) and corrosion products (iron oxides), which evidence the failed tube had suffered corrosion attack. The compound $CaSO_4$ caused coal/fly ash corrosion on the interface of scale/metal tube with a temperature range of 566–732 °C. The compound with low melting point formed molten flux at operating temperature and eliminated oxide layer which led to the tube being exposed. Overtime, metal tube continued to be consumed and a reduction in wall thickness caused it to be nonuniform and damaged. Therefore, it is evident that coal/fly ash corrosion occurred and started with an accumulation of fly ash on the surface of a tube that operated at a temperature of 540–705 °C [12].

Microhardness Results

The hardness test on the failed tube in Table 3 shows variation in hardness on the lip rupture (the location of sample numbers 1 and 2 in Fig. 2) compared to the area away from the lip rupture (the location of sample number 3 in Fig. 2). With respect to the material hardness of ASTM A213 T91, the significant decrease in hardness near the lip rupture indicates that the creep damage and material softening during service had occurred.

Discussions

From the evidence, failure mechanism in secondary superheater tube can be explained further using the following illustration of superheater tube with slag deposits on the outer wall of the tube as shown in Fig. 10.

Flue gas flew upward between the two tubes with slag deposits in the outer wall (see Fig. 10). Slag deposits caused the flue gas flow to be nonuniform where the flow which went through the slag deposits was slower. As the volume of the flue gas stayed the same, the flow

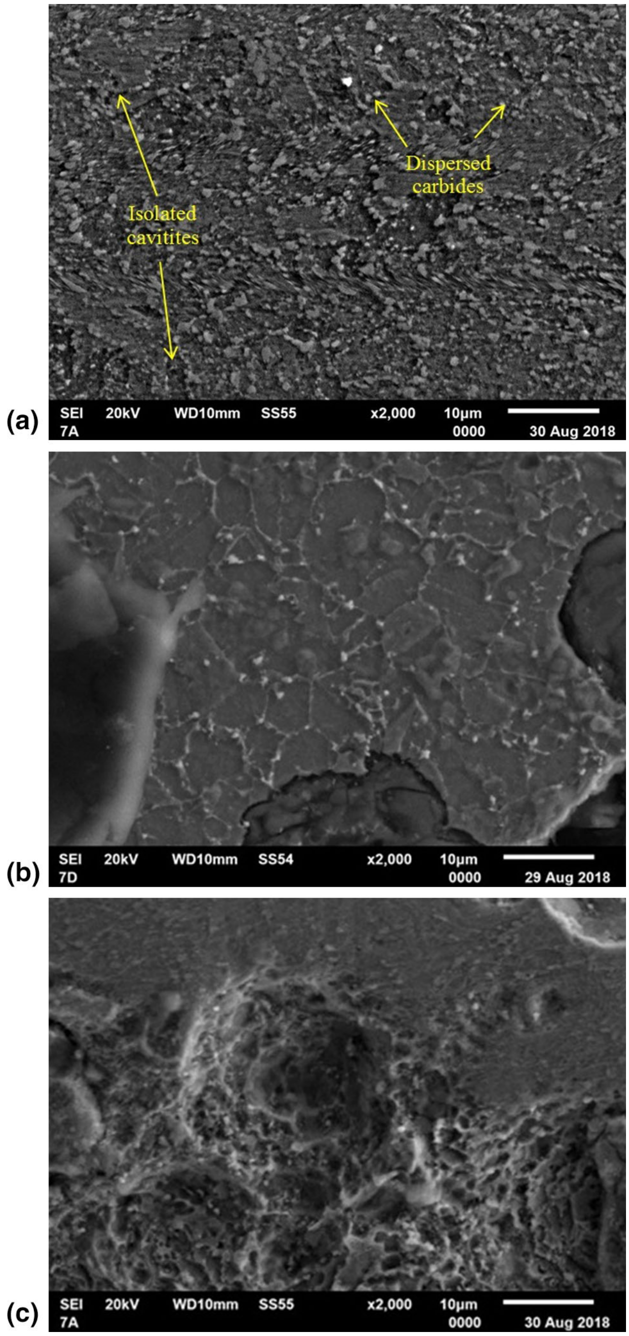

Fig. 7 (**a**) A secondary electron of the SEM image shows dispersed carbides and isolated cavities. (**b**) A secondary electron of the SEM image shows coarse carbides near the lip rupture. (**c**) A secondary electron of the SEM image shows a typical dimpled-rupture fracture surface

which went through areas free of slag deposits became faster and led to turbulence. This then caused localized erosion on the outer wall surface and decrease in thickness nonuniformly in the affected area significantly. The turbulence that occurred in the localized erosion area resulted in the accumulation of heat and led to overheating. It must be noted that the rate of heat transfer in the outer wall with slag deposits was lower than the area which was not covered with slag deposits. This condition caused the outer surface of the tube wall temperature on the area covered by slag deposits to be decreased and the outer surface of the tube wall that was not covered by slag deposits to be increased. The localized rapid overheating beyond the operating temperature drove the flow of material and softened the tube wall. Due to the localized wall thinning and softening of the tube, the tube was unable to withstand the hoop stress with the result that the tube was bent or had a bowed shape (see Fig. 5) leading to a failure due to overloading [1] and resulting in ductile fractures as shown by dimple rupture (see Fig. 7c).

In this case, although corrosion attack had occurred and creep damage was observed, they did not contribute significantly to the main failure of the tube. Hence, it is concluded that the tube failed because of slag deposit formation on the outer surface of the tube wall, which resulted in two simultaneous mechanisms: localized flue gas erosion followed by rapid overheating.

It is clearly evident that the formation of slag deposits on the outer surface of the tube wall is the main cause of the tube failure. It was mentioned previously that the power plant was designed for coal with fly ash temperature of 1300 °C; however, the result of ash fusion temperature test shows that the power plant used coal with fly ash temperature of 1100 °C. The low ash fusion temperature of the used coal was due to the presence of inorganic trace elements as proven by SEM EDS analysis and fly ash content analysis of the slag deposits. If ash fusion temperature is low, ash particles can easily fuse and adhere to the outer surface of the tube wall, forming larger particles and finally causing the slag layer to grow thicker.

Conclusions

Based on the aforementioned data and discussions, the following conclusions are drawn:

(a) The material of the failed tube is satisfied with the specification of ASTM A213 T91 grade steel and suitable for secondary superheater application.
(b) The main cause of failure in the secondary superheater tube was due to the formation of slag deposits on the outer wall of the tube causing two

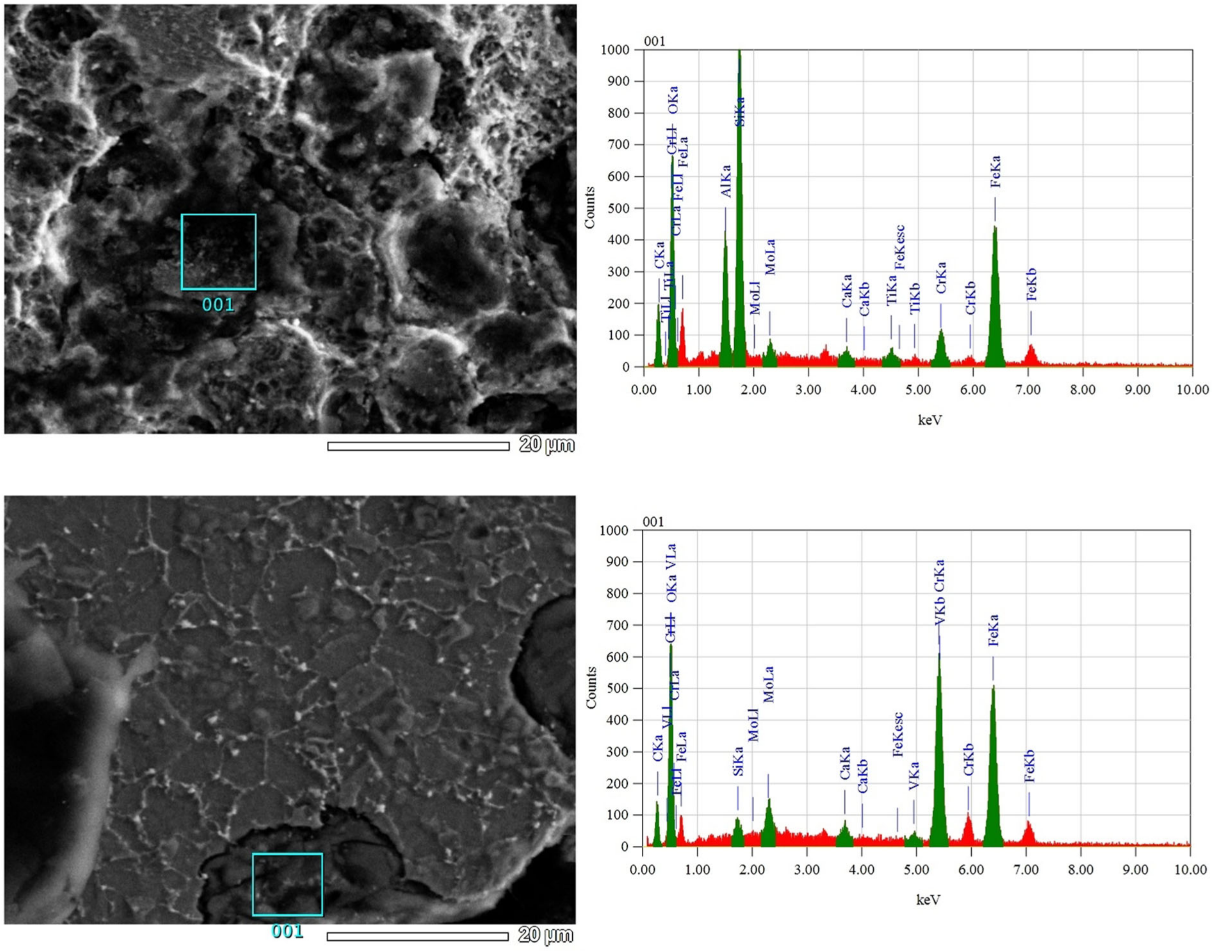

Fig. 8 (**a**) EDS spectrum taken near lip rupture (the location of sample number 1 in Fig. 2). (**b**) EDS spectrum taken near lip rupture (the location of sample number 2 in Fig. 2)

Table 1 SEM-EDS quantitative data on the lip rupture in mass % (the location of sample number 1 in Fig. 2)

Element	% mass
C	18.35
O	30.75
Al	5.48
Si	14.79
Ca	0.45
Ti	0.88
Cr	3.31
Fe	23.80

Table 2 SEM-EDS quantitative data on the lip rupture in mass % (the location of sample number 1 in Fig. 2)

Element	% mass
C	10.51
O	25.10
Si	0.75
Ca	0.77
V	0.75
Cr	24.43
Fe	33.24

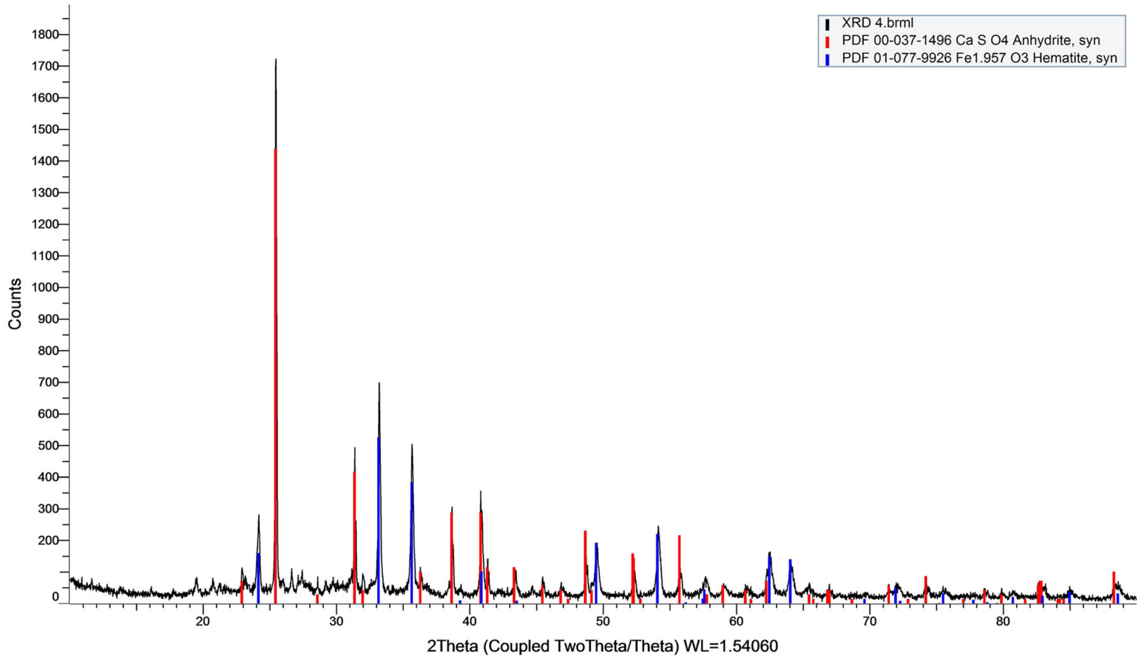

Fig. 9 Characteristic of x-ray diffraction spectrum from slag deposits shows the presence of $CaSO_4$ and iron oxides

Table 3 Hardness data of the failed tube in different locations (for the location, see Fig. 2)

Location	1	2	3
Hardness (HV)	154.0	155.7	191.1

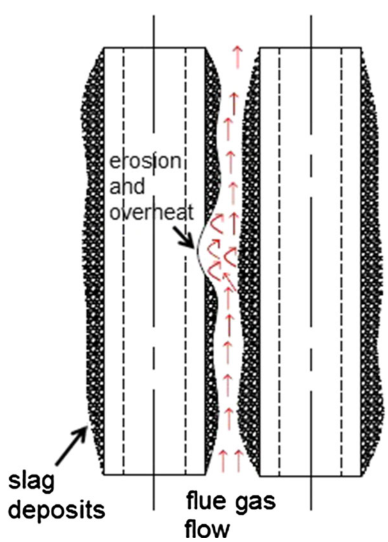

Fig. 10 Illustration of failure mechanism on superheater tube with scale on the outer wall of the tube

simultaneous phenomena that came into play, namely localized flue gas erosion and followed by rapid overheating.

(c) The formation of the slag on the outer surface of the tube wall owing to the ash fusion temperature of the used coal was lower than required coal ash fusion temperature.

Recommendations

Future actions to prevent failures are as follows:

(a) Carry out regular check on air-to-fuel ratio in order to avoid any excess air which can cause incomplete combustion in the superheater.
(b) Use coal with the required ash fusion temperature.
(c) Soot blowing must be carried out periodically and properly according to the manual procedure to remove slag deposits from the tubes.

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