Metallurgical investigation of failed superheater tube used in thermal biomass power plant

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ABSTRACT

This article presents an investigation of a failed superheater tube made of SA210 Grade C used in a biomass power plant. Visual inspection, microstructural examinations, chemical analysis, and hardness measurements were conducted to analyze the causes of the superheater tube failure. The results showed that the failure was mainly caused by long-term overheating, resulting in excessive thermal oxidation and graphitization. Excessive thermal degradation accelerated reduction in the wall tube and facilitated the stresses generated on the tube. Graphitization degraded the microstructure of the tubes, thereby reducing the mechanical performance. The combined effects of severe thermal oxidation and graphitization are attributed to the premature failure of the tube. Therefore, SA213 T22 should be used in the superheated zone. Regular monitoring and inspection of the conditions of the tube is also recommended.

Keywords: Boiler; Failure; Graphitization; Superheater tube.

INTRODUCTION

In typical power plants, boilers are the primary equipment used to generate the superheated steam through the combustion of available fuels (Movahedi-Rad et al., 2015; Peeratatsuwan and Chowwanonthapunya, 2020). Thermal biomass power boilers are considered a considerable choice for electricity production because they help reduce environmental pollution (Jenkins,1989, Mckendry,2020). In addition, this type of energy accounts for nearly 10 % of the renewable energy for electricity worldwide (Mckendry,2002). Technically, superheater tubes are essential components of power boilers (Bahrami et al., 2019 ; Pramanick et al., 2017). They are typically placed in the hottest zone of the boilers and are used to transport superheated steam, which exhibits the highest pressure and temperature. Simultaneously, these tubes are exposed to very high temperatures generated by burning various biomass-based fuels (Fryda et al. , 2010). Using these tubes beyond the design limits for extended periods can result in "long-term overheating,"which subsequently causes microstructural degradation of the superheater tubes. For example, carbon steel tubes can be subjected to "spheroidization," a process by which lamellar iron carbides decompose into spheroidized iron carbides (Chatterjee,2012 ; Liu et al. , 2017). Furthermore, these tubes may be susceptible to "graphitization," in which iron carbides dissociate to form a ferrite matrix and nodular graphite (Perez , 2011). Both microstructural changes negatively affect the mechanical properties. Apart from the microstructural degeneration, long-term overheating can facilitate the transformation of a steel surface to oxide layers, known as "thermal oxidation,". Generally, thermal oxidation causes a wall thickness loss in boiler tubes. Such degradation mechanisms often lead to premature failure of boiler tubes owing to stress rupture (Saha et al. , 2015 ; Ahmad et al. , 2012). Industrially, the failure of superheater tubes is a significant cause of the unplanned power plant outages, resulting in substantial financial losses in different industrial sections [Saha and Roy, 2017]. The failure degradation mechanisms of superheater tubes are complex, and thus far, few studies have been conducted on failed superheater tubes, particularly in the degradation microstructural analysis. Hence, it is necessary to perform failure investigations of the failed superheater tubes, which are imperative for clarifying the microstructural degradation evolution of steel tubes used in biomass power plant and related environments. In this study, a systematic investigation of a failed superheater tube in a biomass fired thermal power plant was conducted. Visual and chemical analysis were conducted on the failed tube. Metallurgical graphics, phase and scale analysis, and hardness measurements in the undamaged and damaged areas were also performed to determine the probable cause of this failure. In addition, the failure mechanisms of the superheater tube were analyzed.

EXPERIMENTAL PROCEDURE

The analysis was performed using the failed secondary superheater tube in a biomass-based power plant. A piece of the damaged tube was obtained for the failure investigation. Under the original condition, the tube had an outer diameter of 33.5 mm and a wall thickness of 4.33 mm. The design temperature for the operation for this failed tube was 540 °C, with the operation pressure of 130 kg/cm^2. SA-213 T22 alloy steel, of which the important alloying elements were Cr and Mo (Xiaowei, 2014; Chowwanonthapunya and Wiriyanon, 2015). The failed tube had been in service for five years. A visual examination of the tube was performed with the naked eye and a moveable enlarging lens to analyse the failure of the tube. Microstructural examination was performed using a scanning electron microscopy (SEM) to obtain further details of the failure.

For the microstructural investigation, mounted samples were prepared from the damaged area of the tube. They were ground on SiC paper down to 1,000 grade emery paper and then polished with a diamond polishing paste of 1 µm. This preparation was performed on as-polished samples. As-etched samples were prepared by etching the polished samples with a 2& nital solution. Both sets of samples were investigated using SEM. A phase analysis of the failed tube was conducted.

using scanning electron microscope equipped with an energy-dispersive spectrometer (EDS). Hardness measurements were conducted on the failed part of the superheater tube to observe the variation in hardness by comparing it with that of the undamaged part. An emission spectrometer was used to determine the chemical composition of the damaged superheater tubes.

RESULTS AND DISSCUSSION

Visual examination

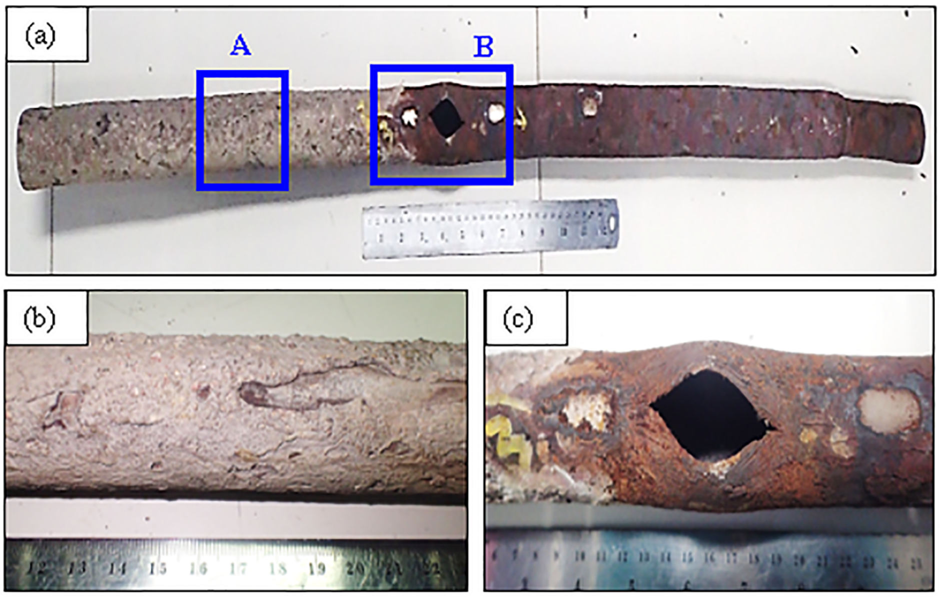

Figure 1. Photographs of failed superheater tube: (a) as-received failed superheater tube, (b) area "A" indicating oxide layers formed on the external surface of the tube and (c) area "B" showing wide-open burst with longitudinal direction

An as-received piece of the failed superheater tube is shown in Figure 1(a). This tube was covered with thick oxide layers in area “A” and a fish-mouth opening of the failed tube was observed at area “B”. Figure 1(b) shows thick oxide layers in area “A”. These thick oxide layers indicate excessive thermal oxidation, which can potentially occur during a long-term thermal exposure. The tube failed with a wide-open burst in the longitudinal direction (Figure 1(a)). The magnified

view of this failed area (Figure 1(c)) indicates thick-lip fish-mouth opening. The thick-lipped opening in the failed area of the tube indicated that the failure was mainly related to long-term overheating, and the tube eventually failed via stress rupture (Ahmad et al. , 2012; Saha and Roy, 2017). The failed tube was sectioned and examined at area 1 and area 2 as exhibited in Figure 2(a), to examine the outer surface conditions of the tube.

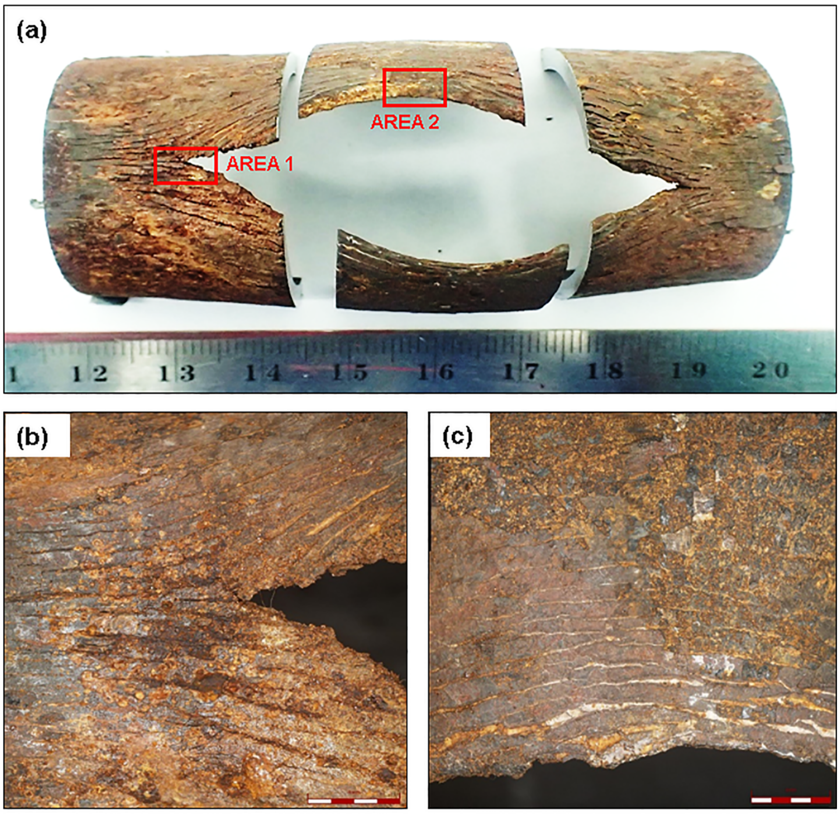

Figure 2. External surface of failed area: (a) failed area covered with oxide layers, (b) oxide layers cracked along tube-axis at area 1, and (c) oxide layers cracked along tube-axis at area 2

Figure 2(a) shows the external surface of the failed area of the tube. The failed area was covered with oxide layers, indicating excessive thermal oxidation. These layers had longitudinal cracks and spallation of oxide layers was also observed (Figure 2(b) and (c)). Typically, long-term overheating generates thermal stress and facilitates tube deformation (Sunandrioa, 2017). Hence,

longitudinal cracks and spallation of the oxide layers in this type of failure contributes to long-term overheating. In addition, the spallation of the oxide layers can cause wall-thinning of the tube, which subsequently generates excessive hoop stress on the tube (Haribhakti et al. , 2018).

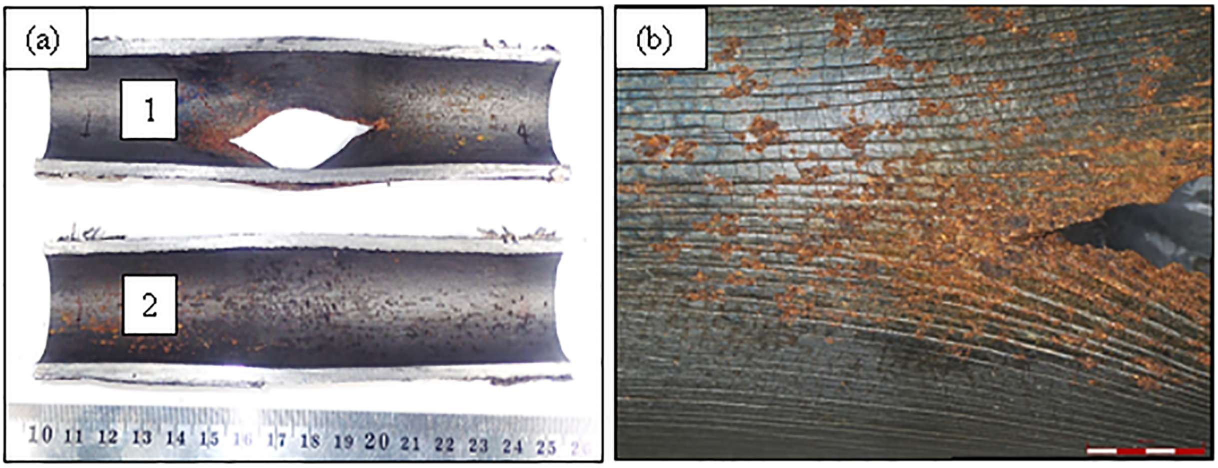

Figure 3. Internal surface of failed tube: (a) tightly adherent scale on internal surface and (b) longitudinal cracks of scale

Figure 3(a) shows the adherent scale on the internal surface of the tube. The longitudinal cracks on scale are shown in Figure 3(b). These cracks were promoted by tube bulging because excessive hoop stress was generated owing to thinning of the outer surface of the tube (Porta and Herro, 1991). Hence, this finding confirmed that the fracture of the failed tub and stress rupture were associated with long-term overheating.

Micrographic examination

A cross-sectional sample for micrographic investigation was prepared from the failed area of the as-received failed tube. The positions for this examination are shown in Figure 4(a). As observed in Figure 4(b), the macrograph of the cross-section at area 1 exhibits a gradual decrease in thickness in the failed tube at the fracture edge, enhancing fish-mouth opening. Figure 4(c) shows

elongated grains near the fracture. These findings indicate plastic deformation before fracture. Microstructural examination was conducted on area 2, located in the mid-wall area of the sample. The results are presented in Figure 5(a) and 5(b). Figure 5(a) shows the microstructure under polished conditions, indicating random dispersion of the nodular-shaped phase throughout the polished matrix.

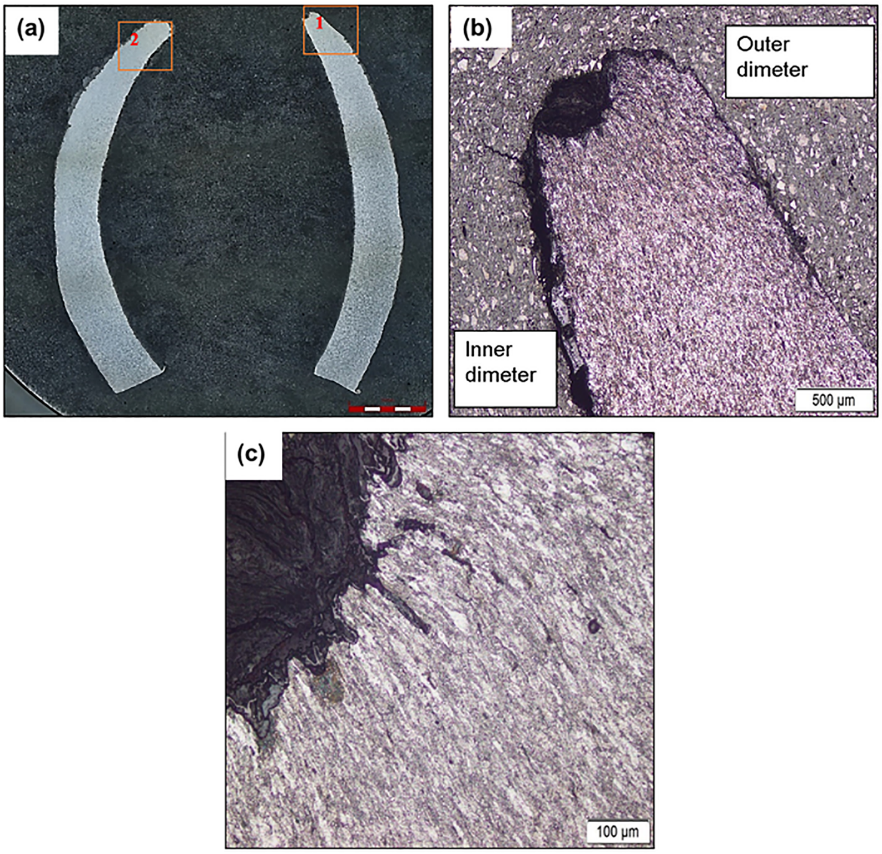

Figure 4. Macrograph analysis at area 1: (a) cross-sectional sample, (b)gradual decrease in thickness in failed tube and (b) elongated grains near fracture

The microstructure of the etched sample prepared from the failed tube consisted of an initial ferrite–pearlite structure with a nodular-shaped phase, as shown in Figure 5(b). A cluster of small nodular-shaped particles was also observed (Figure 5(b)). The presence of the small and large sizes of the nodular-shaped particle indicates the microstructure alternation of the failed tube, known as "graphitization".

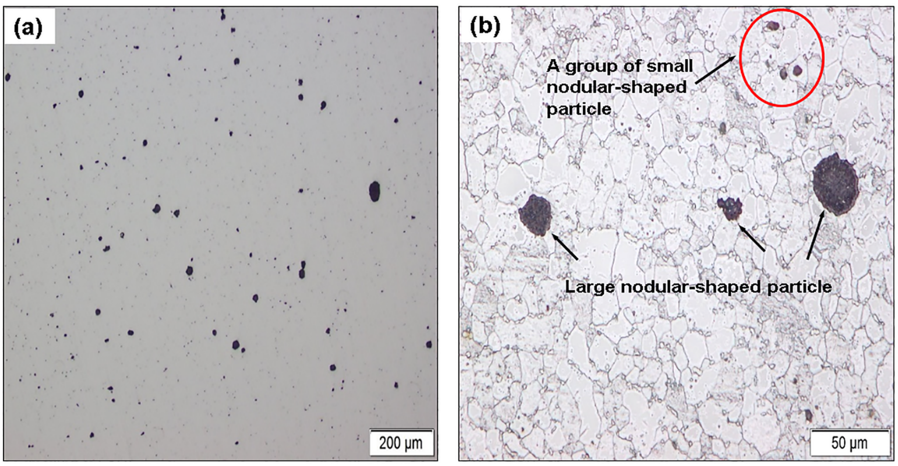

Figure 5. Micrograph analysis at area 2 under (a) unetched condition and (b) etched condition

Figure 6 shows SEM micrographs of a nodular particle. The backscattering image (Figure 6(a)) shows the nodular particle labelled “A”, precipitated on the matrix labelled “B”. The element map overlay (Figure 6(b)) indicates the difference between the nodular-morphology particles and the matrix. Carbon accumulation was observed in the nodular particles. In addition, the distribution of Fe was detected (Figure 6(d)). Therefore, nodular particle A was composed of carbon, which might be nodular graphite. In contrast, the particle matrix consisted of Fe, indicating a ferrite structure. This finding confirms the degraded microstructure and suggests that the nodular-shaped particles observed in the micrograph analysis attributed to the formation of nodular graphite. The presence of small and large nodular-shaped particles indicate the initiation and growth of nodular graphite (Figure 5(a) and (b)). Therefore, graphitization can be attributed to the microstructural degradation of the failed tube. Pearlite is the main microstructure of boiler tubes and consists of lamellar ferrite and cementite (Haribhakti et al. , 2018). Lamellar cementite is responsible for the strength of the pearlite, which is directly related to the load-bearing capacity of the steel tube. However, after prolonged local heating in the temperature range of 427 to 580 °C, pearlite becomes unstable, and the degradation of this phase can take place (Porta and Herro, 1991).

Such extreme heat exposure promotes the transformation of cementite to free iron and nodular graphite, degrading the mechanical properties and pressure-bearing capacity of the heated tube.

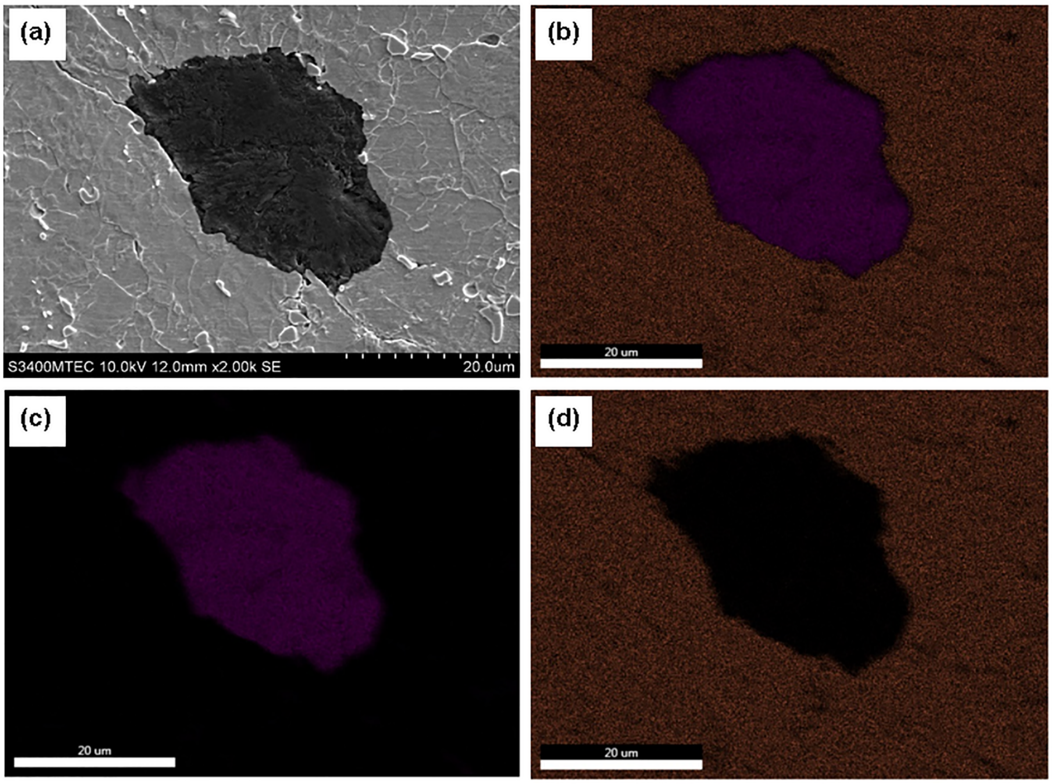

Figure 6. SEM micrograph with EDS analysis of nodular graphite: (a) backscattering image, (b) element map overlay, (c) C distribution and (d) Fe distribution.

Chemical analysis

The chemical analysis was conducted using the spectrometer. The results were summarized and compared with the chemical composition for SA 213 T22 and SA210 Grade C according to ASME, (2019) specification (Table1). The chemical composition of the failed tube differed from that of SA213 T22, the material designed for the superheater tube in this biomass boiler. In contrast, the chemical composition of the failed tube corresponded to that of SA210 Grade C. SA210 Grade C is regarded as carbon steel boiler tube without the addition of significant alloying elements (Prabu et al, 2014).

Table 1. Chemical compositions of failed tube, SA213 T22 and SA210 Grade C

Element	Composition (%wt)						
	C	**Mn**	**P**	**S**	**Si**	**Cr**	Mo
SA213 T22	0.05 - 0.15	0.30 -0.60	0.025	0.025	0.05	1.90 - 2.60	0.87-1.13
SA210 Gr. C	0.350	0.290 - 1.060	0.035	0.035	0.100	-	
Failed Tube	0.305	0.446	0.008	0.021	0.207	< 0.005	0.026

This type of boiler tube can undergo the microstructural degradation when exposed to elevated temperatures for an extended period, particularly, in the superheat zone of boilers. Technically, the combined effects of Mo and Cr added to carbon steels can retard pearlite decomposition and increase the thermal oxidation resistance of carbon steels during thermal exposure (Bahrami et al., 2019). The degeneration of this phase leads to degradation of the mechanical properties and the integrity of the carbon steel boiler tubes. SA 213 T22 is low alloy steel boiler tubes, with significant Mo and Cr contents, which are added to improve the microstructural degradation resistance and thermal oxidation resistance (Haribhakti et al. , 2018 ; Porta and Herro, 1991). Therefore, under the severe operating conditions of the superheated zone, SA-213 T22 as the designed material, exhibits better resistance to the degenerated microstructure and thermal oxidation than the carbon steel boiler tube. The severe environment of the superheated zone in this biomass boiler requires using higher-grade materials. Thus, the carbon steel tube, SA-210 Grade C, used in the superheated zone of this boiler, should be replaced with A-213 T22 to prevent the recurrence of similar failures.

Hardness measurement

Micro-hardness measurements were performed on the failed and undamaged areas of the tubes. The hardness was measured at 7 points, (Figure 7). The hardness of the damaged area was significantly lower than that of the undamaged area. A reduction in the hardness of the failed area typically reflects degradation in the strength and integrity of the failed tube.

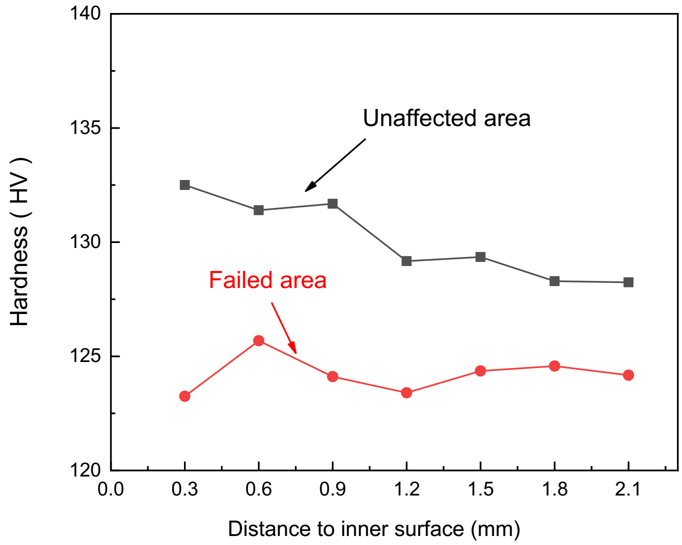

Figure 7. Micro-hardness results obtained from outer to inner surface measurements.

This result indicates the negative effect of prolonged local heating, which consequently accelerates the decomposition of pearlite into ferrite and randomly distributed nodular graphite. Ferrite is softer than cementite. Therefore, the microstructure degradation by the localized heating over a prolonged period of time is attributed to the reduced hardness and strength of the failed area of the damaged superheater tube.

Degradation mechanism

Based on the investigation results, a schematic illustrating the failure of the superheater tube is shown in Figure 8. SA 210 Grade C, which is an inappropriate material, is used in the superheating zone of the biomass boiler. In this zone, the exterior surface of the tube is subjected to thermal exposure and severe environmental conditions from burning biomass fuels. Long-term localized heating results in excessive thermal oxidation, leading to the formation of thick oxide layers. The thermal stress generated by long-term overheating forms longitudinal cracks and spalled patches in the oxide layers covering the outer surface of the tube, resulting in wall-thinning of the tube and subsequent excessive hoop stress on the tube.

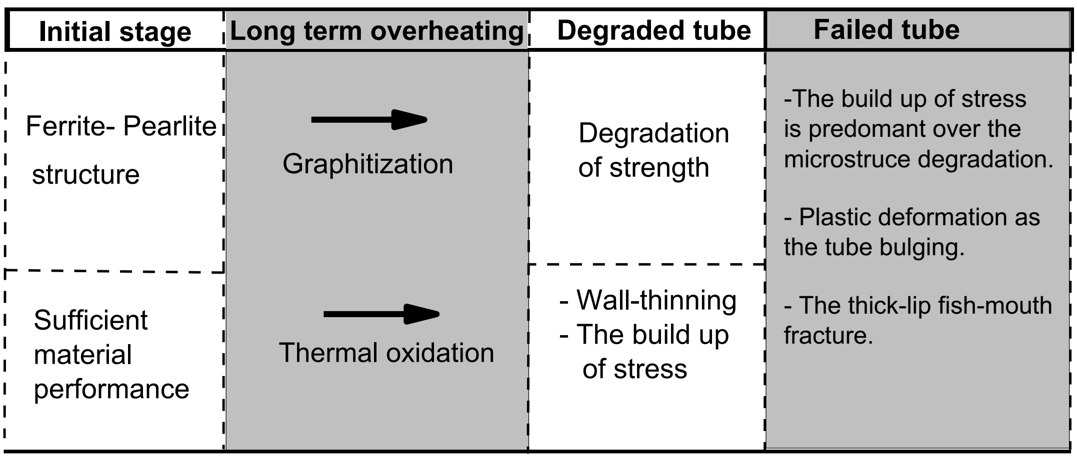

Figure 8. Schematic diagram illustrating failure mechanism of inappropriate material, SA 210 Grade C, used in biomass boiler.

The outer surface of the tube underwent localized heating for a prolonged period, resulting in graphitization of the failed tube, as expressed by Equation (1).

$$Fe_3C = 3Fe + C \quad (1)$$

Graphitization is related to the conversion of cementite (Fe_3C) in pearlite to free iron (Fe) and nodular graphite (C), resulting in the mechanical performance degradation of the tube. As the tube continuously experiences long-term overheating, the wall-thinning process proceeds, generating increased hoop stress in the failed area of the tube. Simultaneously, graphitization occurs, resulting in degraded material performance in the failed area of the tube. When the build-up of hoop stress is predominant over the microstructural degeneration effect, the tube becomes plastically deformed, resulting in tube bulging and failure owning to stress rupture, as indicated by the thick-lip fish-mouth fracture at the failed area of the superheater tube.

CONCLUSION

The failure of superheater boiler tube used in a biomass boiler for five years was investigated. The results showed that this tube mainly failed owing to long-term overheating, subsequently promoting excessive thermal oxidation and graphitization of the tube. Severe thermal degradation resulted in wall tube reduction and increased the circumferential stress. Graphitization degenerated the microstructure of the tube, eventually degrading its material performance. The combination of the effects of excessive thermal oxidation and graphitization was responsible for the failure of the superheater boiler tube. Therefore, it is recommended that the carbon steel tube be replaced with the designed material, SA213 T22, in the superheating zone. Regular monitoring of the external surface of the tube is also recommended.

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