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Study of Microstructure and Mechanical Property Degradation of SA210 A1 Boiler Tube

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Abstract: The comprehension of the microstructure change and mechanical property degradation are of particular importance for assessing the integrity of aging boiler tubes. This paper describes the investigation of microstructure evolution and mechanical property degradation of SA210 A1 steel used in an actual boiler condition. The investigation deals with visual inspection, chemical composition analysis, micrograph study using Energy Dispersive Spectroscopy-Scanning Electron Microscopy (EDS-SEM), tensile test and hardness test. The result showed that the prolonged operating period in the high temperature condition resulted in the reduction of the mechanical properties of the SA 210 A1 steel tube. The study also indicated the presence of the onset of the pearlite disintegration and coagulation, resulted from the microstructure degradation of the aged steel tube after the elevated temperature service in a boiler. It is advisable that the microstructure technique, i.e. metallurgical replica, should be added to the common on-site inspection to increase the effectiveness of the maintenance and maintain the availability of the steam generating units.

Keywords: Degradation, microstructure, mechanical properties, SA210 A1 steel

1. Introduction

Boiler is fundamentally a closed combustion vessel, which is used to generate steam by applying heat from the fuel combustion to water [1-2]. Technically, the tube metal temperature within the combustion chamber of boilers can reach 400 °C or up with the working pressure ranging from 10 to100 bar [2-3]. Such service conditions are obviously severe to materials. Thus, materials of boiler tubes must have good mechanical properties and possess sufficient resistance to mechanical performance deterioration at elevated temperature conditions. SA 210 A1 is one of essential materials for producing heat exchanger tubes in power boilers and heat recovery steam generators [3-4]. This material is a ferritic steel, which can provide acceptable mechanical performance for steam generating systems. Nevertheless, due to prolonged service in the high temperature exposure, this steel tube will be aging continuously and degradation of the microstructure and mechanical performance cannot be avoided [4-5]. Presently, the premature failure of steel boiler tubes becomes one of a critical problem in industries and one of leading causes is mostly related to the high temperature degradation of the steel tubes [6-7].

To maintain serviceability, the annual on-site inspection to examine the boiler tube conditions is required. In practice, the examination of the aging boiler tubes for decision-making in tube replacements often relies on the visual inspection and the comparison of the remaining thickness of the aging tubes with the minimum required thickness of the unused tubes [8]. If the remaining thickness of aging tubes without deformation is thicker than the minimum required thickness, then these tubes can be put into further service [9-10]. This assessment is undoubtedly useful because it is a cost-saving inspection, which can offer the quick guidelines for maintenance activities. However, the

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question bearing in engineers' mind of modern industries is whether the investigation of microstructure changes in the aging boiler tubes should regularly be added to ensure the availability of the steam generating units. Besides, the degradation of mechanical performance and metallurgical evolution of this steel aging in the actual boiler environment are still lacking. Therefore, this research aims at filling the gap and provides more understanding in the degradation of the boiler steel tubes, which can further be the vital information for monitoring and inspecting other boilers in modern industries.

2. Experimental Procedure

This study was based on the degradation investigation of a SA 210 A1boiler tube which had been used as a water wall tube in a power boiler of a petrochemical plant for three years. The bituminous coal was used as a fuel in this boiler unit. The detailed operational conditions utilized during its application are listed in Table 1.

Table1 - Detailed parameters of the used steel tube

Parameters	Range of values
Outside diameter and thickness for the water tube	51.2 mm and 5 mm
Operating pressure	58.8 barg
External temperature	700-800 °C
Internal temperature	250-300 °C

In order to study the degradation of the used steel tube, several tests were conducted. These included visual inspection at the fire and water side of the steel tube, chemical composition analysis, micrograph study using SEM together with EDS analysis, tensile test and hardness test. The unused boiler tube was also employed to be reference materials in this present study. Visual inspection was first carried out to check the surface conditions at both the outer surface (the fire side) and the inner surface (the water side) of the used steel tube. The investigation of the chemical compositions at the outer surface of both steel tubes were performed using spectrometer (model ARL-3460, Serial no. 6318-AD) by referring to ASME SA210 Grade A1 [11]. The samples for the microstructure observation were prepared from both tubes at the inner, the middle, and the outer zone of the tubes. The mechanical performance was measured by the tensile and hardness test. The positions from which the samples for the tensile test were prepared are at 0°, 90°, 180° and 270° of the circumferential direction of the cross section of the tube as shown in Fig.1(a). The tensile test of this test was conducted in accordance with the standard JIS Z2241[12]. The measurement of the hardness at the cross section area of tubes was based on NACE TM 0498-98 [13]. In the hardness test, the constant load of 500 g with the dwell time of 15 seconds was applied at both cross section area and the outer surface of the tubes. The hardness test was conducted at 3 points per quadrant at 0°, 90°, 180° and 270° for the cross section area and the outer surface of the tubes, as shown in Fig.1(b).

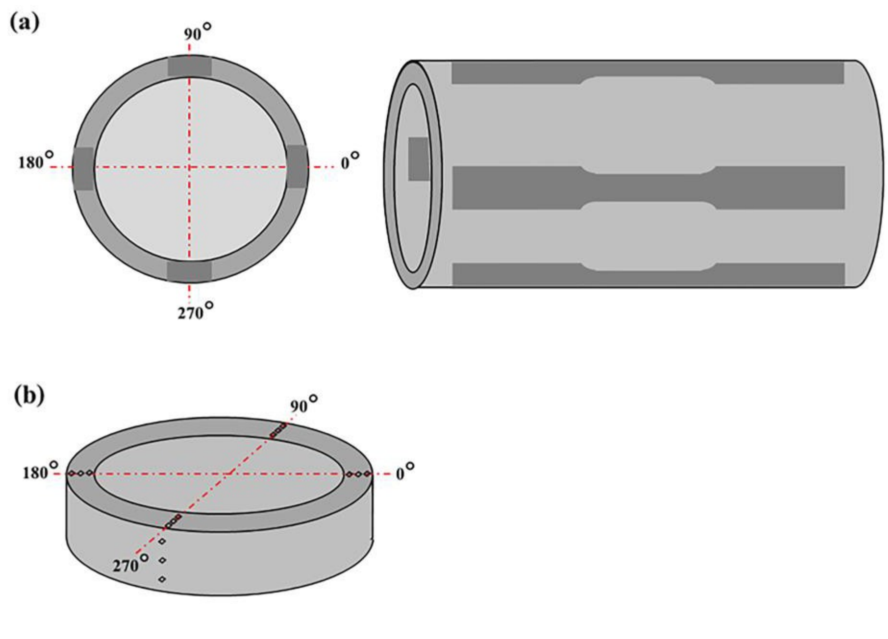

Fig. 1 - (a) positions of the tensile specimen preparation; (b) positions of the hardness measurement

3. Results

3.1 Visual inspections and chemical composition analysis

The visual inspection was initially conducted by evaluating the dimension and the present thickness of the used boiler tube by comparing them with those of the unused boiler tube. Result from the dimension check showed that the used tube had no any significant changes in the outside diameter, as shown in Fig.2. Besides, the present thickness of the used boiler tube showed almost no change with respect to that of the unused tube.

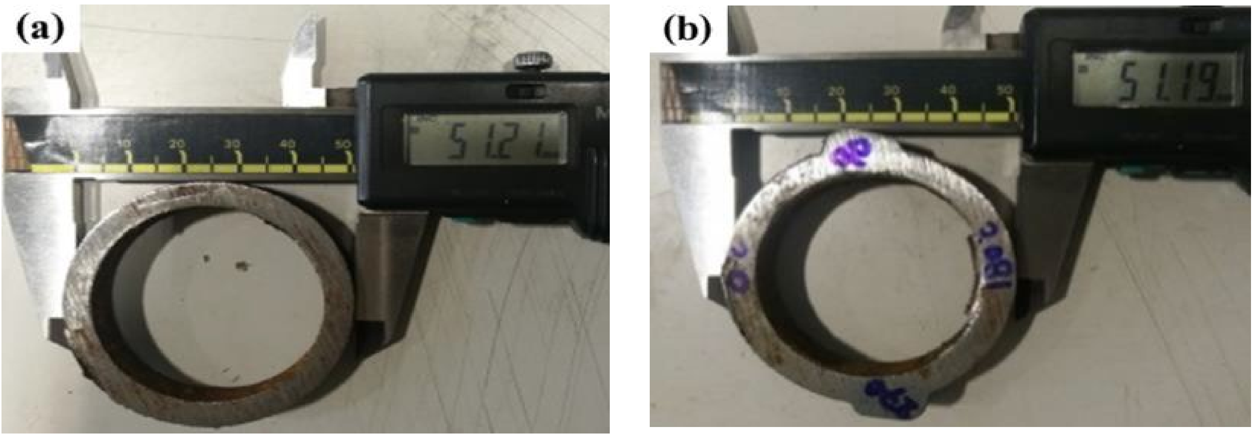

Fig. 2 - The dimension check at the outside diameter (a) unused tube; (b) used tube

The surface conditions at the outer surface of the used boiler tube were investigated and compared them with those of the unused boiler tube as shown in Fig.3. Results from the inspection displayed no signs of deformations, cracking or any discontinuities on the used tube, but the outer surface of the used boiler tube was rougher than that of the new boiler tube. Usually, steel tubes subjected to the elevated temperature environment for prolonged period of the operating time can be oxidized and form the oxide scales [14]. In addition, the combustion environment from the burning of bituminous coal in furnace zone of the boiler can induce the ash deposits [15]. Thus, the appearance of the rough surface can be attributed to the oxide scales and ash deposits accumulated on the outer surface of the used tube exposed to fire. Normally, the oxide scales or deposits covering on the fire side of the used steel tube can lose adhesion and slowly flake, which could lead to the thinning of the tube wall of the boiler tube in the future [14-15].

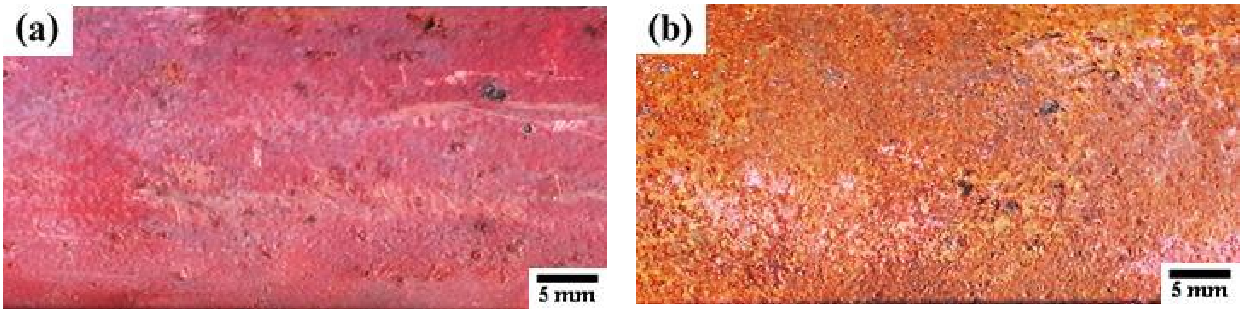

Fig. 3 - Outer surface conditions (a) the unused tube; (b) used tube

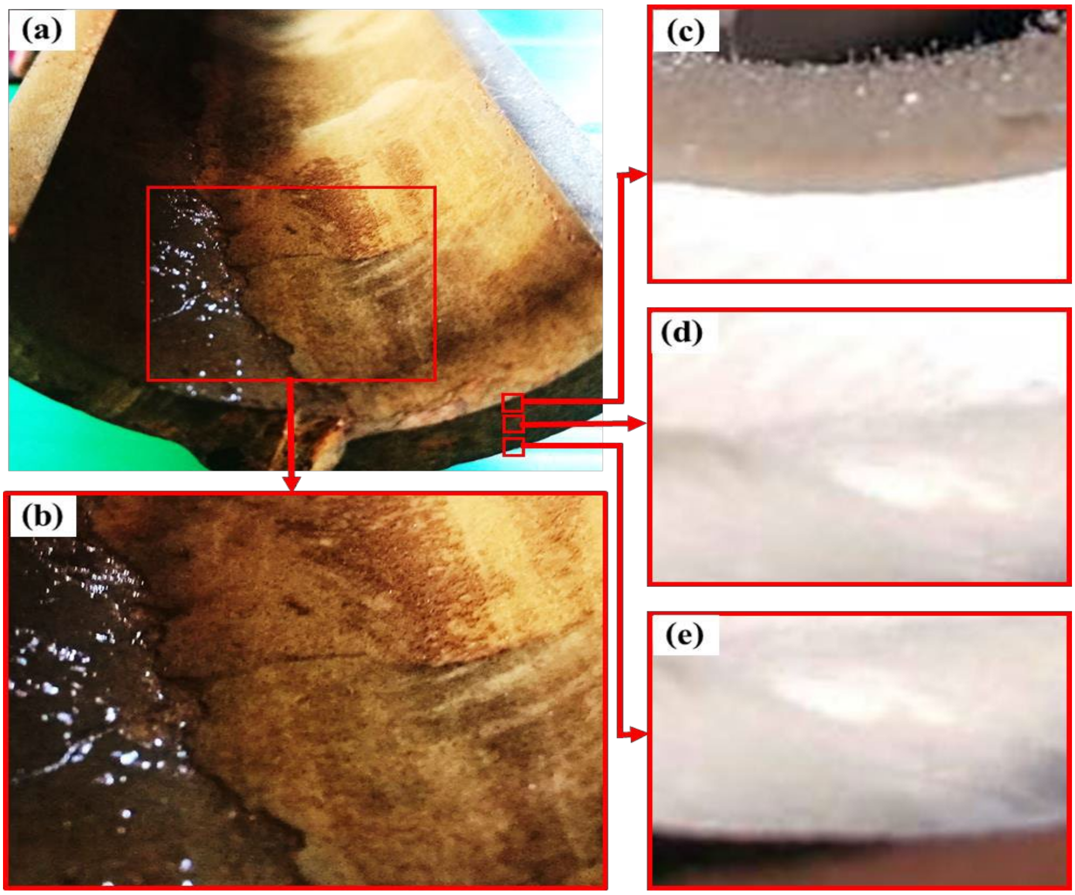

Fig. 4 - Visual inspection for inner surface conditions of the used tube (a) inner surface; (b-e) high magnification views of inner surface

The inner surface conditions of the used tube were investigated as exhibited in Fig. 4. Obviously, the inner surface of the used boiler tube showed no signs of corrosion or any damages even though it was partially covered with the thin scale layers as shown in Figs. 4(a)-(b). This finding may imply that the corrosion deterioration would not be the major problem of the steel used in this boiler. Nevertheless, the water quality should be continuously controlled to avoid the formation of the thick scale layers. The thick layers of scales could lead to the corrosion under deposits or scales in the future. The higher magnification views of the cross sectioned tube were exhibited in Figs. 4(c)-(d), indicating that no discontinuities were found within the cross sectioned areas. The magnification view of the cross sectioned area of the used tube in Fig. 4(e) showed no sign of deformation or any discontinuities, which was agreeable to the results of the visual investigation at the fire side of the used tube.

Table 2 - Chemical compositions (wt.%) analyzed by spectrometer

Chemical composition	C	Mn	P	S	Si	Cr	Mo
Unused tube	0.209	0.417	0.017	0.012	0.197	0.032	0.001
Used tube	0.197	0.451	0.016	0.018	0.217	0.030	0.001

Chemical analysis results in Table 2 revealed almost no change in the chemical compositions of the used tube with respect to those of the unused steel tube. This implies that a three-year exposure in the furnace zone of the boiler did not significantly affect the chemical compositions of the used tube.

3.2 Microstructure examination

The micrographs of the unused and used tube are shown in Fig.5. The unused tube composed of ferrite grains (white area) and nodules of pearlite structure (dark area), while the used tube was subjected to the microstructure morphology change.

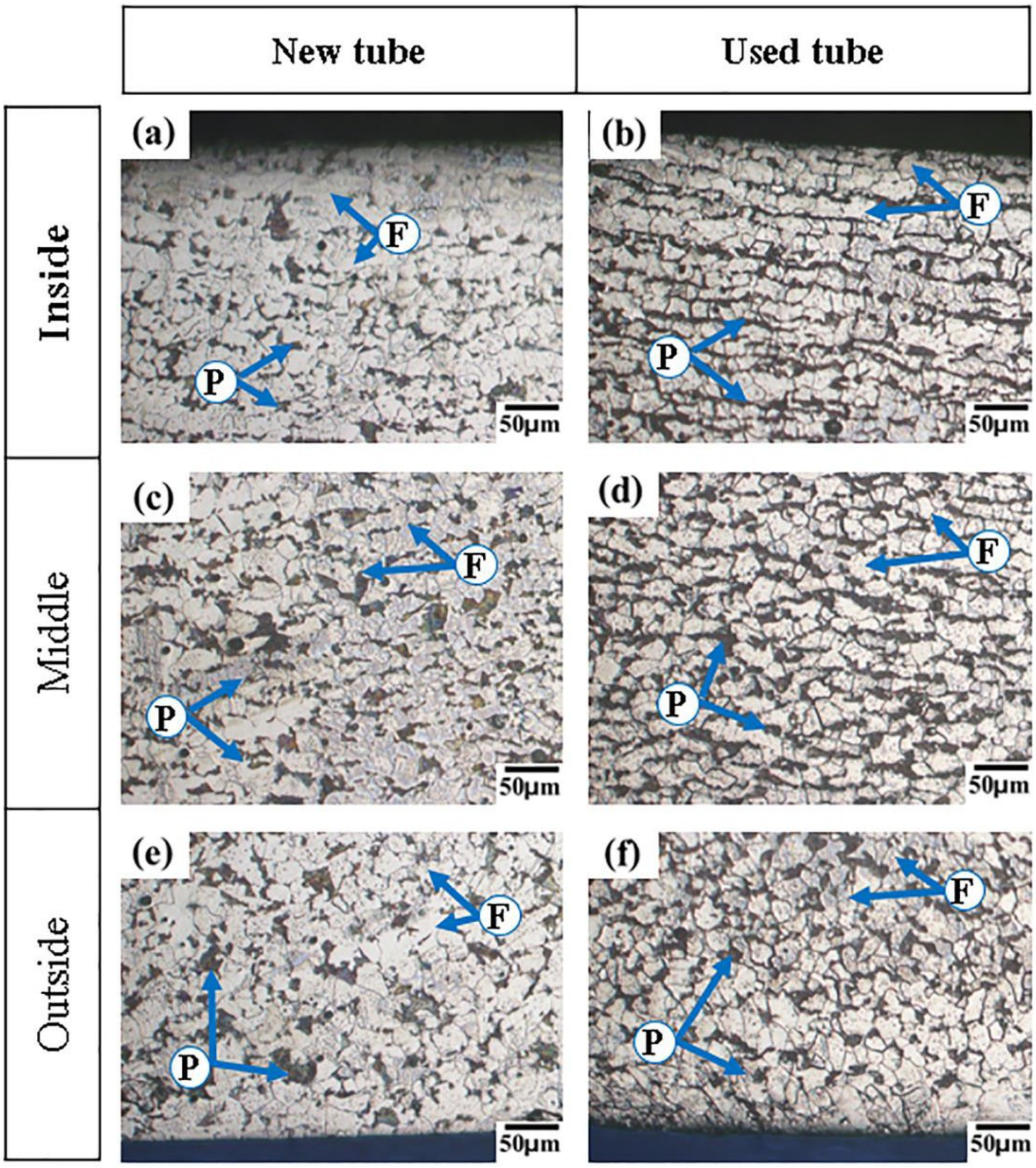

Fig. 5 - Representative optical micrographs of (a-b) inside of the unused and used tube, (c-d) mid-wall of the unused tube and used tube; (e-f) outside of the unused tube and used tube exhibiting black regions of pearlite (P) and white regions of ferrite (F)

As seen from Figs. 5 (d) and (e), the changes in shape and size of pearlite at the inside and mid-wall of the used tube were obvious. These findings mean the first step of the microstructure change and indicates the beginning of the pearlite disintegration. The microstructure morphology observation of the outside of the used tube in Fig. 5(f) exhibited the first step of the pearlite coagulation. Basically, SA 210 A1 is a low carbon steel which contains the mixture of ferrite and pearlite. [16-17] Pearlite is usually considered to be less stable than ferrite, especially when carbon steel is heated for sufficiently long time [18]. Thus, the high temperature service condition in the furnace zone of the boiler causes the degradation in microstructure morphology, resulting in the onset of the disintegration and coagulation of pearlite.

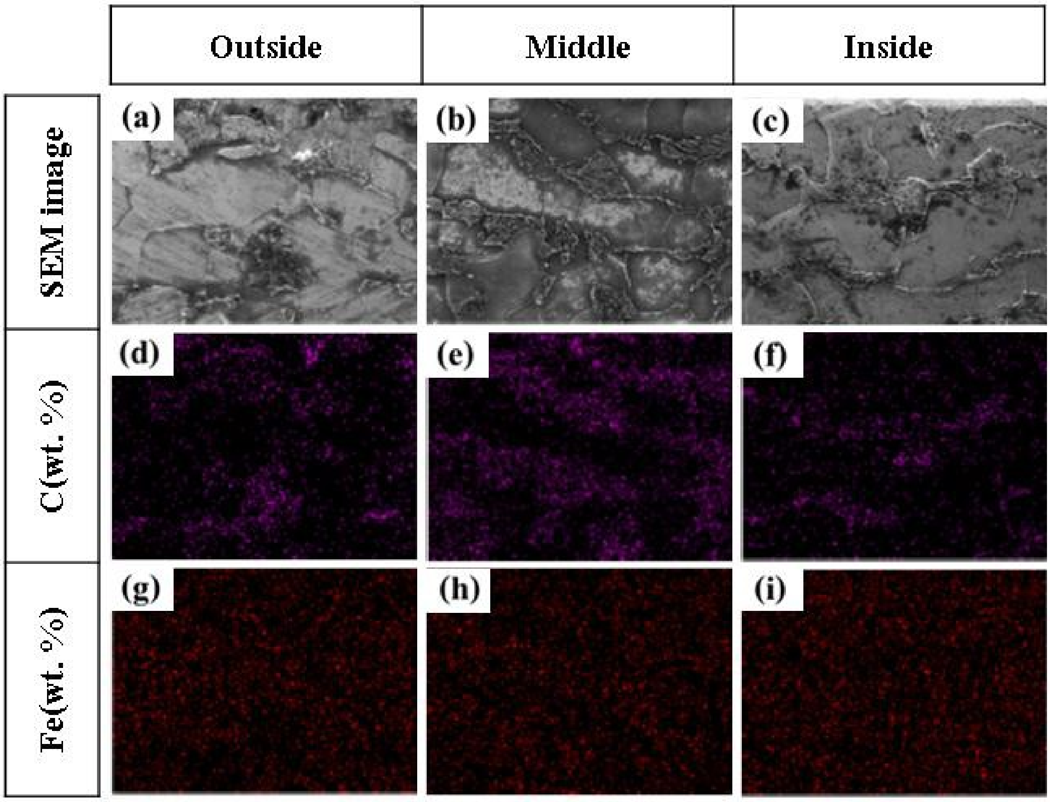

Fig.6 - SEM micrograph together with EDS analysis of used steel tube (50X) of outside, mid-wall, and inside of the used tube (a -c) SEM image, (d-f) Distribution of carbon; (g-f) Distribution of ferrous

SEM micrographs of the used steel tube from the outside, mid-wall, and inside are exhibited in Figs. 6 (a), (b) and (c). SEM micrographs of the used tube apparently indicated the changes of the pearlite morphology. Obviously, the pearlite phase containing in the outside of the used tube tended to be coagulated, while the shape of pearlite observed at the mid-wall and the inside of the used tube tended to be disintegrated by distributing at the grain boundary of ferrite. Carbon and ferrous distribution in the used steel at the outside are shown in Figs. 6 (d) and (g) and those of mid-wall, and inside of the used tube are provided in Figs. 6 (e) and (h) and Figs 6 (f) and (i), respectively. Clearly, the ferrous distribution showed the uniform dispersion throughout the matrix of all of investigated areas. However, the distribution of carbon illustrated the accumulation of carbon where pearlite phase exists. At the outside steel tube, carbon tended to locally aggregated. This possibly indicates the change of the pearlite shape and confirms the finding of the beginning of the pearlite coagulation in Fig. 5(f). In the mid-wall and the inside of the used tube, carbon tended to be distributed along the grain boundary of ferrite. This also means the change of the pearlite morphology and supports the finding of the disintegration of pearlite, as illustrated in Figs. 5(b) and (d). The findings of the coagulation and the breakdown of pearlite in the degraded boiler tubes were also discussed by several authors. U.K. Chatterjee et al [19] showed the imprints of the pearlite coagulation and disintegration in the plain carbon tubes used in the boiler. J.Ahmad et al [20] investigated the failure of the carbon steel tubes used at the furnace zone of a boiler unit and found the dispersion of coagulated pearlite throughout the microstructure of the steel. Thus, the findings of the microstructure degradation of the boiler steel tube in this present study are in accordance with results of accepted investigations.

3.3 Mechanical performance examination

Fig. 7 reveals results from tensile test of samples prepared from the unused and used steel tube. Clearly, tensile strength, yield strength and elongation measured from the used steel tube at 0°, 90°, 180° and 270° were lower than those from the unused steel tube. Usually, tensile and yield strength are two essential properties that can be used to characterize the strength of material [21-22], while elongation is used to indicate the ductility [23-24]. Hence, the steel tube exposed to the high temperature environment of the boiler was subjected to the degradation in the strength and its ductility.

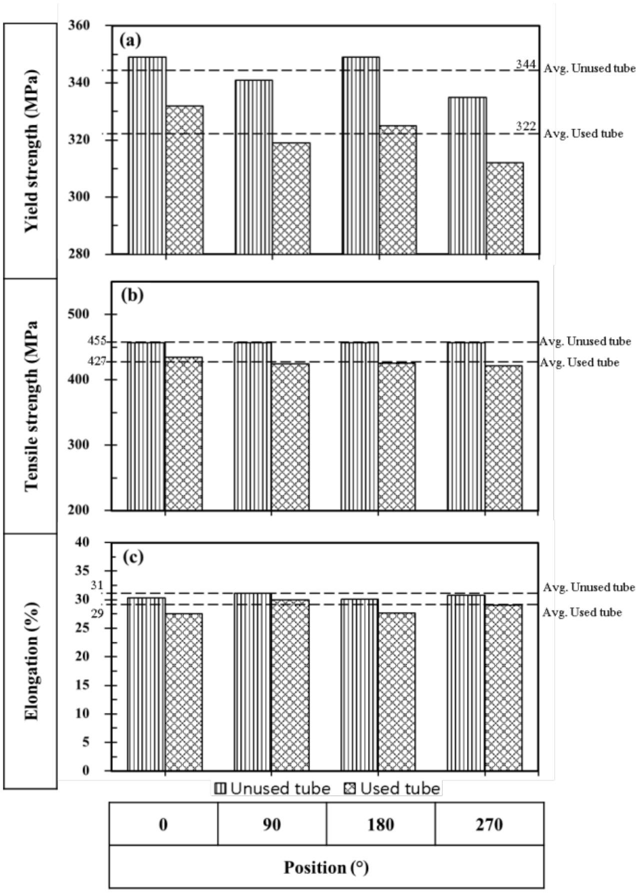

Fig. 7 - Results from tensile test of unused and used tube (a) yield strength, (b) tensile strength; (c) elongation

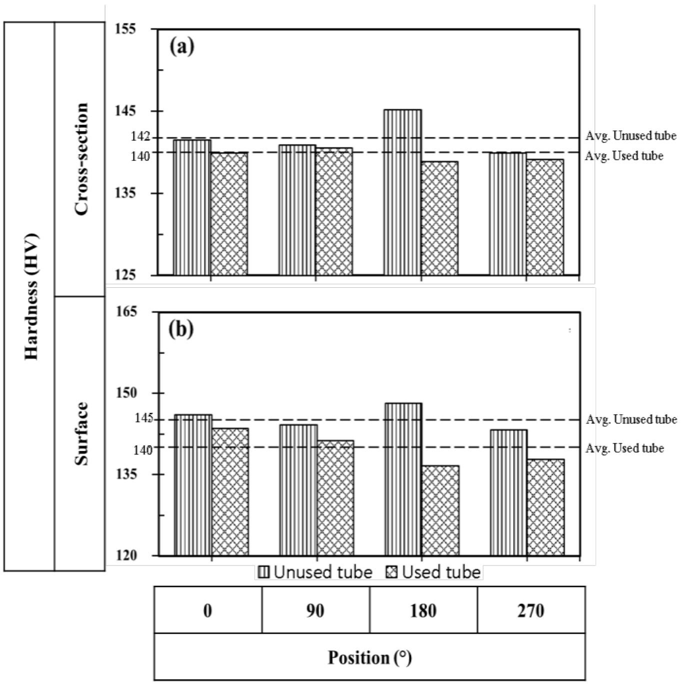

Fig. 8 - Results from hardness test of unused and used tube (a) Cross-section; (b) surface

Hardness test was performed at the surface and the cross section area of the unused tube and used tube. The results shown in Fig. 8 indicated the reduction of the hardness of the used tube with respect to that of the unused tube. All of the reduction in the mechanical performance of the used steel tube can be attributed to a significant consequence of the changes in the microstructures of the boiler tubes.

4. Discussion

To gain more understanding in the mechanical property change of the used steel tube, the average measured tensile strength, yield strength, elongation, and hardness at the surface and cross section area of the unused tube, used tube and those required by ASME SA210 A1 [11] were given in Table 3.

Table 3 - The comparison of mechanical performance of unused tube, used tube and ASTM standard

Properties	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%EL)	Hardness at surface (HV)	Hardness at cross section area (HV)
Unused	455	344	31	145	142
Used	427	322	29	140	140
Standard	> 415	> 255	> 30	< 145	< 145

From Table 3, it is obvious that the unused tube possessed the acceptable mechanical properties. However, the mechanical performance of the used tube became lower than that of the unused tube. The observation on microstructure morphology of the used tube evidently indicated the changes of the microstructure as shown in Figs 5 and 6. Hence, the degradation of mechanical performance of SA 210 A1 tube aged in the long term heating in a boiler was found to be related to its microstructural change. Based on the aforementioned results, the schematic diagram in illustrating the microstructure and mechanical degradation of a degraded SA 210 A1 tube subjected to the combustion of the bituminous coal in a boiler is given in Fig. 9.

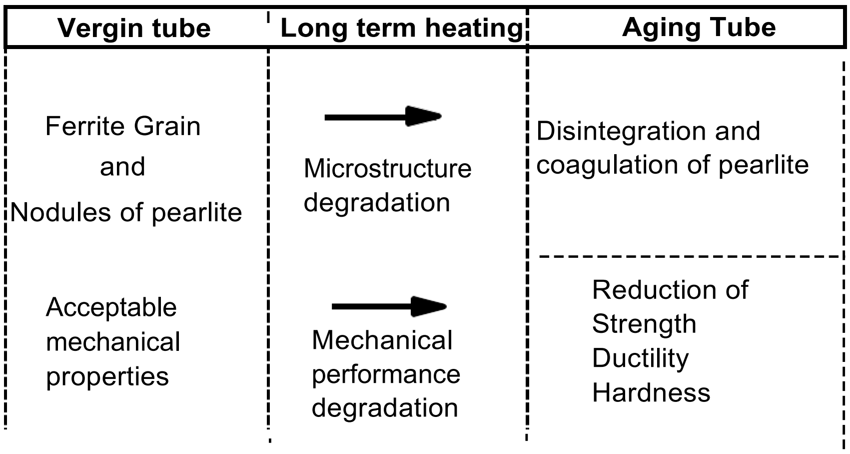

Fig. 9 - The schematic diagram in elucidating the microstructure and mechanical degradation of SA210 A1 steel subjected to an actual boiler environment

Initially, the virgin steel tube contained the ferrite grains and pearlite nodules and its mechanical properties were agreeable to those required by ASME SA210 A1. Nevertheless, after exposed to the high temperature service in a boiler for three years, steel tube turned aged. The oxidation of the surface of the outside steel tube was observed by the visual inspection. However, the significant changes of pearlite morphology was clearly indicated by micrographs and SEM with EDS mapping. The high temperature played essential roles in alternating the pearlite morphology from a nodule shape to disintegrated and coagulated pearlite, causing the decreased mechanical performance of the aging SA210 A1 tube. Basically, the on-site inspection to evaluate the mechanical integrity of the boiler tube conditions is carried out just by visual inspection and the remaining thickness measurement. In practice, the microstructure change inspection is normally not included. In this present study, results from visual inspection indicated that no essential damages were found in the used tubes. Besides, almost no changes in the outside diameters, the thickness of the used tube and chemical compositions were obviously noticed. Conditions obtained from the visual inspection mean that this used tube can further be used. However, results showed that the microstructure changes occurred, resulting in the degraded mechanical properties of the aging steel tube. The longer boiler tubes are exposed to elevated temperature service, the more metallurgical changes and mechanical performance degradation of the tubes will occur. Therefore, it is advised that the microstructure observation technique such as metallographic replica techniques should be employed as a supplementary inspection, especially at the areas where the localized heating or flame impingement potentially take place. The microstructural investigation technique together with the common inspection potentially provides the efficient inspection plans and effective follow-up maintenance activities for power boilers in industries.

5. Conclusion

The degradation of a SA 210 A1boiler tube which had been exposed to the actual boiler environment for three years has already been investigated. Results from the visual inspection revealed that the oxide scales accumulating on the outside of the used steel tube and no changes in the outside diameters, thickness of the used tube and chemical compositions were found. The investigation using micrograph and SEM with EDS mapping exhibited the change of microstructure. Nodule shape of pearlite was changed to be disintegrated and coagulated. The mechanical performance of the used tube decreased with respect to that of the unused tube. The decreased mechanical properties can be contributed to the change of the microstructures of the aging steel tube, which had been exposed to the elevated temperature environment for prolonged period of the operating time. The microstructure observation technique, i.e. metallographic replica techniques, should be regularly added to the common on-site inspection to increase the effectiveness and ensure the good availability of the steam generating units.

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