Graphitization damage on seamless steel tube of pressurized closed-loop of steam boiler

Nur Farhana Hayazi¹, Shaiful Rizam Shamsudin¹,²*, Rajaselan Wardan¹,², Mohd Syazwan Muhamad Sanusi¹,² and Farah Farhana Zainal¹,²

¹School of Materials Engineering, Universiti Malaysia Perlis, Kompleks Pengajian Jejawi 2, Jejawi 02600 Arau Perlis.
²Center of Excellence Geopolymer & Green Technology (CEGEOGTECH), School of Materials Engineering, Universiti Malaysia Perlis, Kompleks Pengajian Jejawi 2, Jejawi 02600 Arau Perlis.

Abstract. The pressurized closed-loop of steam boiler has been in operation for five years has experienced leakage problems at the bottom of the reducer and at the center of the tube on weldment. The metallographic analysis found that the leakage was due to the degradation of microstructure as a result of long-term overheating. The degraded microstructure of the tube boiler material dominated by graphitization. The graphitization normally applicable at 450°C, but with high-pressure water flow (90 bar) in the combination of internal stress on the tube material due to the welding process as well as the formation of the reducer, making the boiler operating temperature is sufficient to produce graphitization. The leakage occurred when the chain and accumulated graphitization happen because the cavities that covered the graphite facilitates the cracking propagation due to the presence of stresses.

1 Introduction

The pressurized closed-loop of steam boiler has been in operation for five years. The boiler uses a reverse osmosis (RO) water without any chemical additives. Pressure and operating temperatures are 90 bar and 290 - 320°C respectively. The boiler tube was found leaked in April 2018 at the bottom reducer. Subsequently, the second leak was also found at the bottom reducer in opposite direction to the first leak some times in May 2018. Followed by the third leak on July 2018 on the bottom plug due to the air trap. Finally, the fourth leak was found on October 2018 at the center tube on weldment. The failed boiler has been dismantled from its location (Figure 1).

Pressure and temperature play an important role in degradation mechanism for alloys such as plain carbon, medium carbon and high alloy steels which has been used in different process of plant application. The microstructure of steel stipulates the properties of metallurgical, physical, mechanical and corrosion. The degradation will occurred, when microstructure is exposed to high pressure-high temperature [1].

*Corresponding author: farhanahayazi@unimap.edu.my
The principle of degradation mechanisms that could be detected by metallography analysis is the microstructural degradations for example graphitization [1], spheroidization of pearlite [2], creep, thermal fatigue, hydrogen attack, carburization, grain boundary oxidation and embrittlement of microstructure etc [3]. Typically, the condition of a boiler is measured by in-situ metallography technique (known as replication testing). In the current situation, as the failed tubes are quite severe, therefore the sampling was carried on the adjacent tube (Figure 2a). The objective of this analysis are to investigate the failure evidence presented by the boiler tube, to understand the graphitization of the graphite nodules through the microstructural changes.

Fig. 1. Camera photograph of the failed boiler component that been dismantled from its location.

2 Methodology

As-received boiler tube was cross-sectioned into 9 workpieces in according to Figure 2b. The samples for chemical composition analysis was marked as OES whereas metallography analysis and hardness measurement were marked as A, B, C, D, E, F, G and H respectively. The chemical composition was analyzed by using optical emission spectrometer, OES (Q8 Magellan, Bruker) at five different spots on the metal surface. The hardness and metallography samples were ground and polished. Hardness measurement was carried out by Rockwell hardness tester (Brevetti Affri, 206 RTD) in HRB scale for each section vertically (Figure 3). Then the polished samples were etched using 2% nital solution to reveal the microstructural pattern on the samples. The analysis was carried out by metallurgical microscope (BX41, Olympus). The morphological analysis was carried out by scanning electron microscope (JSM-6490LV, Jeol).
Fig. 2. (a) Sampling was carried adjacent to the failed tube as shown by red arrow marks and (b) schematic diagram of a sampling section of the as-received boiler tube.

Fig. 3. The location of hardness measurement points.
3 Results and Discussion

The chemical composition of boiler tube material is in compliance with both DIN 17175 St 35.8 and ASTM A192 of the seamless steel tubes for boiler industry where the C has a maximum value of 0.17%. The hardness profile was presented in the Figure 4 below. The results were then compared with standard specification of ASTM A192 (HRB 77). In overall, the hardness level of each sections and directions are significantly inconsistent. The highest hardness is recorded on G sample (HRB 82.4 ± 1.6) which is at the reducer section. It is above the standard specification of ASTM A192. A significant uneven hardness also observed along the circumference of the tube cross-section. At certain direction, the hardness of vertical cross-section is slightly higher than the standard specification of ASTM A192 especially on sample D and H. This proved that there are significant microstructural changes in each vertical sections and the directions of the boiler tube wall due to the non-uniform of the heat distributions along the boiler tube from top to the bottom.

![Hardness profile](image)

Fig. 4. Hardness profile (HRB) on as-received boiler tube for every vertical section

Note: The circumference of the tube cross-section on 8 points namely north (N), northeast (NE), east (E), south-east (SE), south (S), south-west (SW), west (W) and north-west (W). It should be noted that the front tube surface facing the fire flame (N direction) is considered as a hotside whereas the back onto tube surface (S direction) is marked as the cold side.

The microstructure of boiler tube is found to be degraded in term of graphitization and spheroidization of pearlite. Figure 5 shows the degradation begins when iron carbide particles in the ferrite matrix decompose into relatively small graphite nodules (A), growth to be globular graphites (B) followed by coarsening of carbides (C). The significant graphitization is depicted by the planar distribution of graphite nodules occurred at (D) section that located near the weldment. The chain graphitization is detected on (A) section.
Figure 6 shows the enlarging of graphitization from nodular (E) to globular graphite (F). The spheroidization of pearlite also detected in the (F) metal matrix as depicted by the sphere black dot. It occur when the shape of pearlite was migrated from an irregular to a sphere left behind the ferrite ductile matrix. The most extreme graphitization occur on reducer section (G) followed by small radius tube (H). The graphitization occurs at strange microstructure and a higher level of stress region at (G) and (H) sections. These microstructure observation were found to be consistent with the hardness profile in Figure 4. The hardness results can be summarized to be in the range of HRB 73 and HRB 83, whereby the average hardness from the ASTM A192 is HRB 77.

Graphitization is sort of cavity that contains nodules graphite in it (Figure 7a). This cavity is the root cause to the point of weakness of the steel tube matrix. The resulting spheroidite structure is a microstructure that contains sphere-like cementite particles. Spheroidite structure is easy to be ground and polished because of its ductile properties as compared to graphite nodules (Figure 7b).

![Fig. 5. Optical metallographs on sample sections at hot side N direction (↑=shell side): (a) A, (b) B, (c) C & (d) D.](image-url)
4 Conclusion

The boiler tube is in compliance with either DIN 17175 St 35.8) or its equivalent (ASTM A192). The microstructural degradation of tube boiler materials is dominated by graphitization rather than spheroidation of pearlite. Generally, graphitization is applicable at 450°C, but with high-pressure of water flow (90 bar) and internal stress on the tube material due to the welding process and the formation of the reducer, the boiler operating temperature is sufficient to produce the graphitization itself. Graphitization forming cavities containing the structure of the
carbide iron graphite is uniformly dispersed in the ferrite matrix rarely causes failure. Nonetheless, the most dangerous is when chain and accumulated graphitization occur because the cavities that covered the graphite facilitates the cracking propagation due to the presence of stresses as described above. Different hardness in each vertical section and tube direction is due to the different microstructure changes lead by graphitization.

The author would like to acknowledge the support from the Prescott Engineering & Services Sdn Bhd, Pasir Gudang, Johor, Malaysia. Thanks to the School of Materials Engineering & Universiti Malaysia Perlis for providing a special financial support for enabling the publication of this manuscript.

References

1. I. U. Perez, T. L. Silveira, T. F. Silveira, H. C. Furtado, J. Fail. Anal. and Preven. E 11 (2011)
2. N. Nutal, C. J. Gommes, S. Blacher, P. Pouteau, J. P. Pirard, F. Boschini, K. Traina, R. Cloots, Image Anal Stereol. E 29 (2010)
3. G. R. Lobley, W. L. Al-Otaibi, Adv. Mats. Res. E 41-42 (2008)