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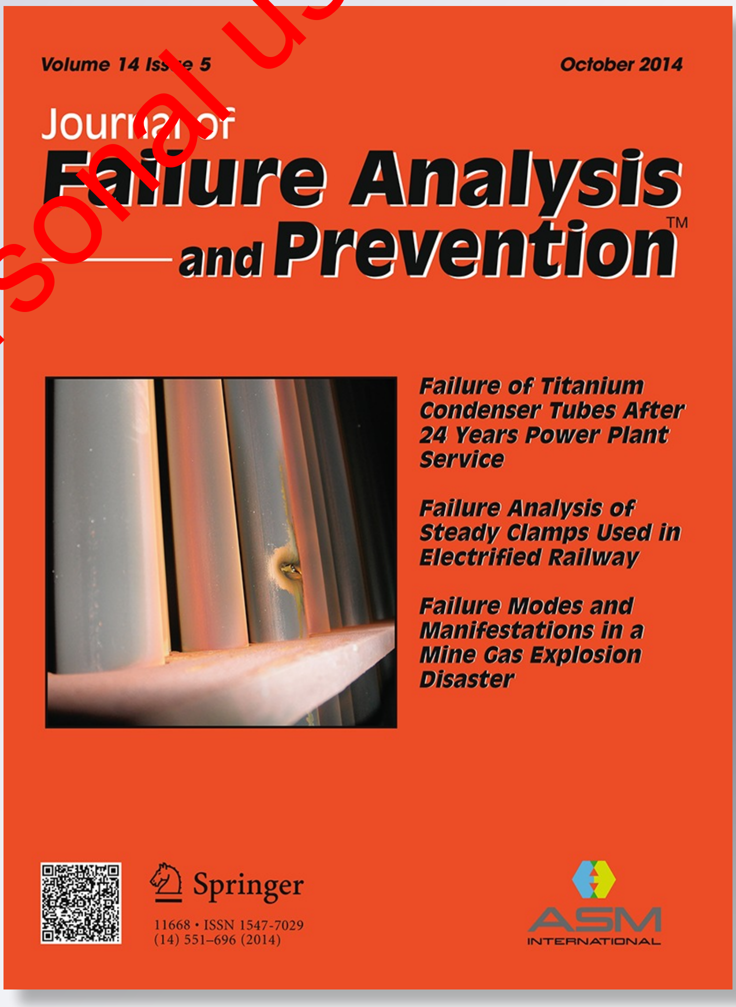

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TECHNICAL ARTICLE—PEER-REVIEWED

Investigation of Leakage on Water Wall Tube in a 660 MW Supercritical Boiler

M. Nurbanasari · Abdurrachim

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Abstract The leakage of a supercritical boiler tube has been investigated. The leakage was observed during a working pressure hydrostatic test under 40.1 MPa. The internal geometry of the investigated leaking tube was multi-lead ribbed tube. Various methods for investigation namely radiography, microstructural analysis using optical and scanning electron microscopes, Vickers hardness testing and chemical analysis were conducted to investigate the main cause of leakage. The results revealed that the material tube met the standard for supercritical boiler tube (ASTM A 213 Grade T12). From the microstructural analysis, there was a crack, which initiated from the outer wall adjacent to the weld metal and propagated to the inner wall of the tube. The crack was due to a weld defect known as "excessive melt through" which is due to overheating during the welding process in joining the tubes. It is suggested that control of welding process parameters must be accomplished during fabrication to make a furnace wall, and placing strip of steel between the tubes to reduce the fit-up gap should be considered.

Keywords Supercritical boiler tube · Leakage · Multi-lead ribbed tube · Microstructure

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Introduction

Supercritical boilers work under the pressure range of 230–265 bar and there is no transitional stage between water and steam. High pressure operation of the boiler aims to upgrade the thermodynamic efficiency. There are four important components in a supercritical boiler namely high-pressure steam piping, headers, superheater tubing, and waterwall tubing [1] Those components need to use special grade material with specific requirements. ASTM A 213 Grade T12 is one of the special grade materials that are suitable for boiler tubes [2]. The application of that material in a power plant has also been reported [3]. This material has good creep strength, and its working temperature is limited to 560 °C [4]. During fabrication, hundreds of boiler tubes are welded together to make a furnace wall.

This current work reports the investigation of leakage on the waterwall tube in a 660 MW supercritical boiler. The tube was multi-lead ribbed and has the outside diameter and the wall thickness, as well as the rib height of 35, 7, and 1 mm, respectively. Each section of tube was welded with a vertical tubing arrangement, and an arc welding process was performed to join the two external surfaces of the tube permanently. The vertical water wall design is aimed to improve heat transfer [5]. This boiler was still undergoing a trial stage before it was ready to be used. The tube leak was observed during a hydrostatic test, which was conducted to certify the condition of the boiler before producing steam. Five leaks were observed on the water wall tubes, when the working pressure reached 20 MPa. An Investigation was initiated to find the main cause of leakage before the supercritical boiler was used.

Investigation Method

The investigation began with on-site visual inspection during hydrostatic testing to detect the location of the leaks and to collect the samples. The leaking tubes were cut for further investigations. The methods for investigation were as follows:

a. Radiography was conducted based on ASME Boiler and Pressure Vessel Code Section V [6].
b. Chemical composition was analyzed using optical emission spectroscopy (OES-Master Pro-Oxford Instrument).
c. A microstructural analysis was performed using optical microscopy and scanning electron microscopy (SEM). Optical microscopy used a Nikon Epiphot and SEM was conducted on a JEOL 610-LA operated at 20 kV. Samples for microstructural analysis were prepared using standard metallographic techniques with an etchant solution of 5% nital.
d. Hardness was measured using a Vickers Hardness Tester with load 200 g and dwell time 15 s.

Results and Discussion

Visual Inspection

From the on-site investigation, five leaks were found at different locations on the water wall, and some of them are shown in Fig. 1. Further investigation was carried out by cutting the leaking tubes (Fig. 2).

Figure 2 presents the investigated tubes in which leakage was observed in between tube parenting material and the weld metal (indicated by a yellow rectangle). The cross section of the leaking tubes (Fig. 2b) shows the inner surface geometry of the tube is ribbed.

Verification of Tube Material

The type of tubes was seamless, and from the longitudinal section, the inner surface geometry was spiral or multi-lead ribbed (see Fig. 3).

Chemical composition of the tube using OES is presented in Table 1. The results were then compared with the standard specification of ASTM A 213 Grade T12.

From the data in Table 1, it can be seen that the material of the tube was in good agreement with ASTM A 213 Grade T12. The maximum hardness value for A 213 Grade T12 is 163 BHN, which is equivalent to 170 HV [2]. The hardness value of the leaking tube was 160.7 ± 3 HV, which is below the maximum allowed by the standard.

Figure 4 shows the parent material microstructure of a leaking tube taken near the external surface. The microstructure consisted of equiaxed ferrite and banded pearlite. The banding was a consequence of hot deformation, and it suggests that the tubes had experienced a hot extrusion during the manufacturing process. From chemical composition, hardness data, and microstructure of the tube, the

Fig. 1 The leaking water wall tubes in a 660 MW supercritical boiler

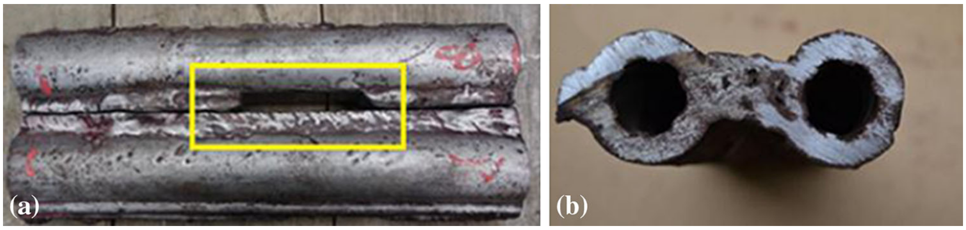

Fig. 2 Leaking tubes with a yellow rectangle indicating the leak location (**a**) and cross section of leaking tube (**b**)

material of the leaking tube met the standard specification for supercritical boiler tube (ASTM A 213 Grade T12).

Radiography Inspection

Radiographic testing on the leaking tubes was carried out to detect discontinuities. Although there was a difference in contrast, the radiographic test result was not sufficient as it did not show clearly any evidence of leaking, cracking, and/or typical welding defects of the tubes. To find the source of the leaks, the welded tubes were separated in longitudinal section, and then each tube was ground starting from the surface of the welded zone until the cracks appeared, as illustrated in Fig. 5.

Figure 5a shows the welded tubes that were cut in longitudinal section. After grinding on the surface of the leaked tube-A, it was clearly seen that there was a crack that might be a leak path (indicated by red circle in Fig. 5b). Tube-A was chosen for deeper investigation. To get more detail of the crack path, the tube was cut gradually as presented in Fig. 6.

Figure 6a shows the cracks on the tube-A, and the longitudinal section of the tube revealed that there was a defect on the inner surface of the tube (Fig. 6b) as shown by an arrow. It is believed that the crack seen in Fig 6a was initiated from the external surface in welded zone and propagated to the inner surface of the tube, causing a gap inside the tube material as a source of leakage. For confirmation, the sample was divided into two sections in the cracked zone in the transverse direction, as indicated by the dashed line in Fig. 6b.

Fig. 3 Inner surface geometry of a leaking tube showing typical multi-lead ribbed geometry

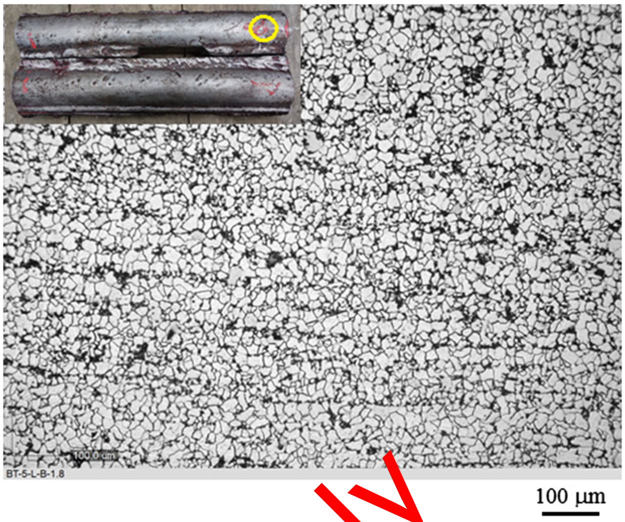

Fig. 4 An optical image of leaking tube microstructure (inserted figure shows a sample taken for microstructure analysis)

Both Fig. 6c, d give strong evidence that the cracks occurred from the external surface on the side of the welded tube and propagated to the inner surface. Microstructural analysis with a scanning electron microscope on the sample in Fig. 6d was carried out to supplement these observations (Fig. 7).

Figure 7 shows various microstructures taken from different areas around the leak. The overall section is shown in Fig. 7a. The microstructures of the parent material tube, which can be seen in Fig. 7b, f show that the grain structures are homogeneous equiaxed ferrite and pearlite. As this sample was taken from the transverse plane, the equiaxed ferrite and no seam on the tube indicate that this tube was a hot extruded product. Figure 7 also shows that the welding process was carried using multipass method, which is indicated by multiple heat-affected zones (HAZ). The Fig. 7c reveals that the grain structures in the HAZ were finer than those of the parent material (Fig. 7b, f) due to repeated heating [7]. Note that in multipass welding, a weld zone is replaced by a HAZ of subsequence passes. Figure 7d shows a cavity observed in the section. This cavity seems to have formed during the welding process. There was improper welding parameter or procedure control causing overheat in a local area. As a result, excessive penetration occurred and the tube material melted going

Table 1 Chemical composition of the investigated tube (wt.%)

Remarks	C	Si	S	P	Mn	Cr	Mo	Fe
ASTM A213	0.05–0.15	0.5 (max)	0.025 (max)	0.025 (max)	0.3–0.61	0.8–1.25	0.44–0.65	Balance
Leaking tube	0.13	0.31	0.01	0.01	0.47	0.94	0.52	Balance

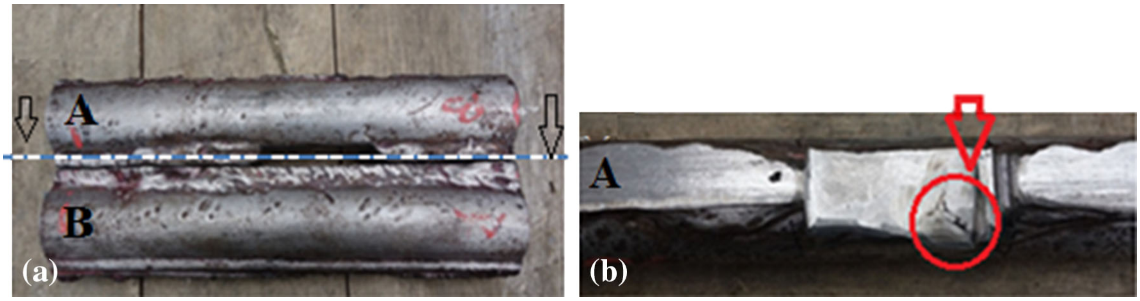

Fig. 5 The leaking tubes were separated in the longitudinal direction as indicated by the dashed line (A and B) (**a**) and cracks appeared after grinding on one of the separated tubes (**b**)

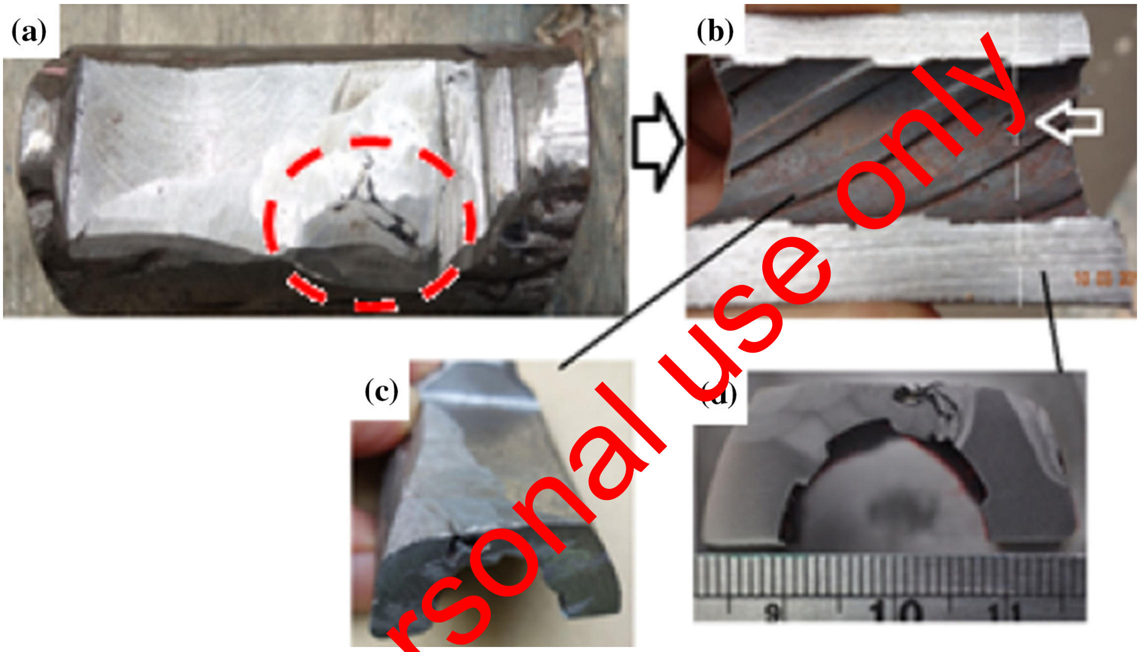

Fig. 6 Section of tube in the longitudinal direction (**a**, **b**, **c**) and section of tube in the transverse direction after polishing (**d**)

through the inner surface of the tube. Overheating during welding also caused gas easily to be trapped in the melted material producing a cavity. At the same time, the flux of the electrode was also trapped in that area (Fig. 7e). Figure 7e shows a completely different microstructure than the others (Fig. 7c, b, f). These features are typical of a weld defect known as *excessive melt through* or *burn through* [8]. This weld defect is caused by incorrect parameter welding, resulting in overheat, or the fit-up gap between the tubes to be joined is too large [8].

The hardness of the sample was in the range 154–243 HV. The lowest hardness value (154 HV) was in the parent material and the highest hardness value was near the weld zone. The difference in hardness is due to the difference in cooling rate. The higher cooling rate results in the higher hardness value. The highest cooling rate was at weld zone, followed by the HAZ.

Conclusions

The findings of the investigation verified that the tube material met the standard. The main cause of leakage on the water wall tube was the formation of a weld defect known as *excessive melt through* or *burn through*, which was attributed to improper welding parameters or process variable control during fabrication.

Recommendation

It is suggested that leakage could be avoided by controlling the heat input through the welding parameters during fabrication of the furnace walls. The distance between the tubes to be joined must be also considered. The weld joint design was butt and the gap between the external surface of the tube has the range of 5–10 mm. It seems that using a

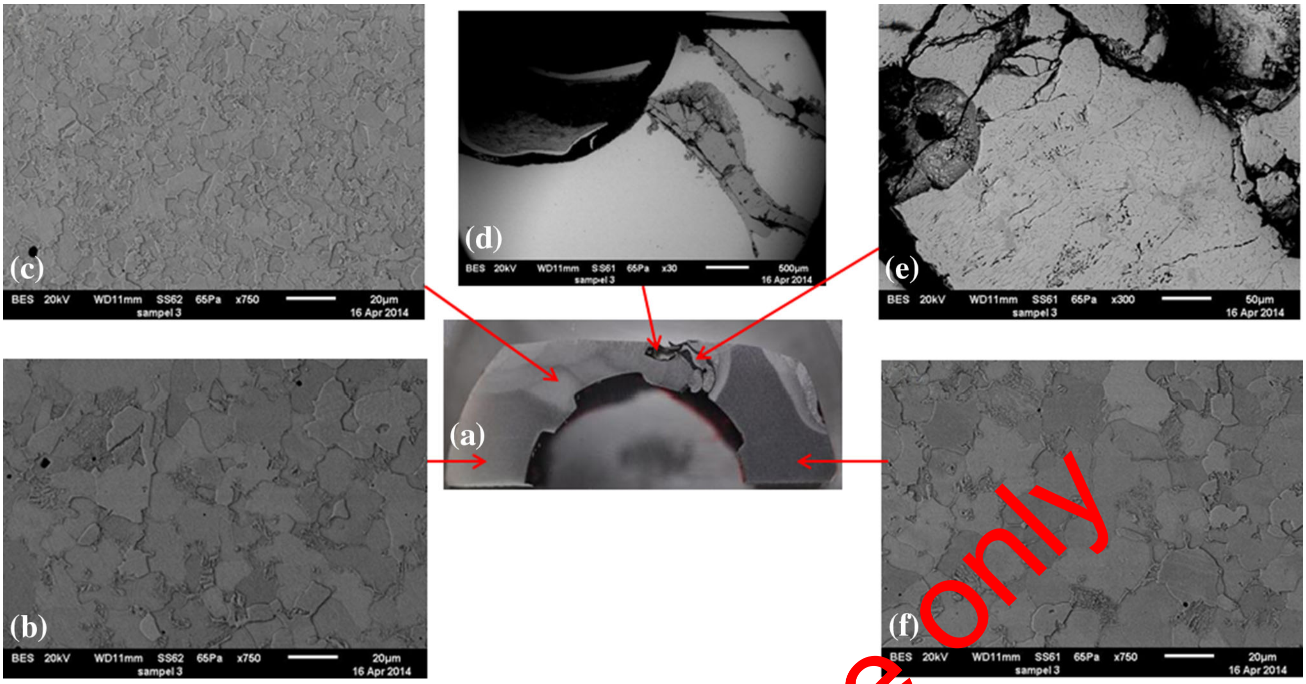

Fig. 7 Back scatter electron images showing microstructures in various areas (for letters, see the text)

steel plate between the two tubes to provide a smaller fit-up gap could be implemented.

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