Failure analysis of an economizer tube sheet & its cover due to corrosion and imperfection

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Abstract. The boiler's economizer was found to be inefficient. Corrosion is suspected to be the source of the economizer's pressure reduction. The examinations included visual inspection, stereomicroscope, metallography, elemental microanalysis by EDS, and chemical composition analysis. The economizer failed due to a weld crater caused by improper welding, which induced residual welding stress. The slight sulfur content of the condensed or flue gas that causes rusting on the economizer's outer cover is not considered a severe failure issue. Material SUS304 stainless steel is the right selection for economizer materials.

1 Introduction

A boiler economizer is a heat exchanger that saves energy or provides functional activities like preheating a fluid. Flue gases contain nitrogen, carbon dioxide, water vapour, soot, carbon monoxide, and sulphur [1]. The recovered heat is used to preheat boiler feedwater, which is subsequently turned into superheated steam. Economizers contribute to the overall efficiency of the power plant. Thermal power stations utilize economizers to minimize their energy generation costs [2].

The failed boiler economizer in this investigation was made from SUS 304 stainless steel. After nearly five years of operation, the control room manager noted that the boiler system's total pressure was steadily declining. A first inspection revealed minor leaks in the boiler economizer. Initially, only a tiny amount of water vapour was shot out. After a few days, the economy eventually burst. Initially, the leak was deemed minor and expected to be readily repaired by the plant's maintenance crews. However, the leak became so widespread in the economizer that it had migrated to other locations and was impossible to manage. The plant engineers decided to dismantle the economizer tube sheet and wall cover to determine why it was leaking. Figure 1 shows the camera photographs of the boiler economizer's tube sheet.

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and wall cover surfaces after disassembly. The disassembled components were then transported to a lab for root cause examination.

![Camera photographs of (a) the tube sheet, (b) the water-side wall, and (c) the outer cover surface of the boiler economizer reveal regions of imperfection indicated by red arrow marks.](image)

It is critical to investigate the reasons for a boiler component failure to avoid future losses. In addition, identifying the proper failure mechanism often helps in ensuring the equipment's integrity. Boiler tube failures may occur for various reasons, including water and steam-formed deposits, overheating, corrosion, welding flaws, hydrogen damage, thermal & stress-related failure, cavitation, material deficiency, etc. [3,4].

In some case histories, Nazim Mohamed et al. [5] reported catastrophic pipe failure of a steam generator after 20 years. Erosion-corrosion, material degradation, and weld flaws all contributed to the pipe failing. The increased pressure resulted in transverse failure of the coated weld defects. Cracks along the longitudinal axis allow steam to escape, resulting in increased corrosion. Saragi et al. [6] also reported that evaporation produces stress corrosion cracks, residual stress, fractures, and tube surface thinning in riser tubes and tube economizers. Combustion emissions, strain hardening, and erosion produce stress corrosion, as shown by intergranular-transgranular cracking. Ghosh & Roy [7] stated that graphitization is the root cause of the failure since the temperature exposure of the platen water wall tube of the economizer was high for a long time. Other cases are as reported by Corleto & Argade [8], where a heat exchanger was used to test different weld failures. The circumferential weld connecting the carbon steel shell to the duplex stainless steel tube sheet broke when H$_2$S was introduced into the exchanger. Sulfide-stress corrosion cracking was facilitated by high weld hardness and local chemical dispersion.

This study aims to determine the failure mechanism of a failed boiler economizer and provide appropriate preventative measures.

2 Investigation Procedure

A visual examination was conducted using a digital DSLR camera (D3100, Nikon) to capture the boiler economizer's original condition. A stereomicroscope (SZX 10, Olympus) was used for the close-up examination. The sample was cross-sectioned and ground up to 1000 grit of SiC grinding paper before being polished with a 6 and 1-micron diamond solution. A metallurgical microscope (BX41M, Olympus) was used to inspect the as-polished surface for the presence of defects and/or microstructural abnormalities. Once etched, the material's microstructure was viewed under a metallurgical microscope (BX51M, Olympus). The elemental analysis of the metal surface was carried out qualitatively using a SEM's energy dispersive spectrometer, EDS (Oxford INCA Energy EDS system). Finally, the chemical composition of the metal surface was determined using an optical emission spectrometer, OES (Q8 Magellan, Bruker).
3 Results & Discussion

The investigation began with a visual inspection of the boiler economizer's tube sheet and water-side wall cover, which revealed a welding bead that needed to be highlighted. A crater defect has been detected in several locations throughout this region (Figure 2). Camera photography depicts the welding fault on the weld beads at the tube sheet (Figure 2(a)) and the water-side wall cover (Figure 2(b)). Craters can be distinguished visually by their concave weld profile (bead). It occurs during the final solidified weld pool and is frequently coupled with a small amount of gas porosity. In the top view, it can be seen in Figure 2(c) that the morphology of the weld crater is grumbling with a blackish-brown colour and a white residue precipitate, which is believed to be the result of an oxidation interaction with the operating environment. In addition, the rusting has also left a brownish-reddish stain on both the tube sheet and the water-side wall cover surface.

![Fig. 2 Camera photographs of the typical crater defect welding bead on (a) tube sheet & (b) water-side wall cover as well as (c) close-up view on crater defect.](image)

On closer inspection, it can be observed that the crater defect has produced a cavity inside the weldment due to an insufficient quantity of molten metal being utilized to fill the hollow and formed a thin portion of the weldment (Figure 3). As a result of a lack of molten metal, a crater seems to be a weldment with a circular excavated hole on the base metal surface. Furthermore, there was no obvious corrosion failure as early as had been anticipated. This type of corrosion comprises just homogeneous rusting with no pitting defects or uneven surface characteristics.

Figure 4 depicts observations made with a stereomicroscope in the region of the crater defect. An internal crack was discovered in the tube sheet (Figure 4(a)), and inward cracking was also detected on the wall cover sample (Figure 4(b)). This finding was already predicted since the weld end (crater site) undergoes considerable shrinkage during cooling, resulting in high residual stress. Figure 4 also confirms that no corrosion failure has been detected as it shows a smooth surface without any pitting or irregularities.

The investigation was extended by analyzing the crack behaviour that occurred near this crater defect. The results of the metallographic analysis shown in Figure 5 show there are hairline, branching and transgranular cracks. It confirms that the metal undergoes residual stress due to welding activity. Figure 5 (a) shows a slightly winding primary transgranular with branched cracks in the tube sheet wall. On the other hand, the crack in the cover wall was microscopically showing a branch with multi-directional hairlines at the ends of primary transgranular cracks (Figure 5(a)). These signs are due to residual stresses produced in welded components whenever plastic deformation occurs due to forces exceeding their elastic limit.
Fig. 3. Closed-up camera images of cross-sectional view on (a) tube sheet and (b) cover wall crater defect.

Fig. 4. Stereomicroscope images of as-polished surface on (a) tube sheet and (b) cover wall identified the internal cracking defect due to residual welding stress.

Fig. 5. Optical metallographs of an etched surface at the crack region on (a) tube sheet and (b) cover wall.

The presence of corrosion agents in the economizer was investigated using energy dispersive spectroscopy to determine the role of corrosion in economizer failure (EDS). Figure 6. depicts the EDS pattern, which displays the key elements present in the area under study. Corrosive agents do not seem to be present on the surfaces of the water-side walls. The brownish-reddish colour is caused by homogeneous corrosion or rust on the metal surface due to the oxidation process occurring on the metal surface (Figure 6(a)). On the other hand, the existence of trace sulphur elements on the outer cover wall surface was ascribed to the presence of sulphur content in the condensation or flue gas as marked by the red circle in Figure 6(b). It was believed to be the cause of the corroded surface on the outer cover wall.
surface. After a thorough examination has shown that no corrosion-associated failures such as pitting or stress corrosion cracking have occurred during the investigation, uniform corrosion or rust is not regarded as an uncommon occurrence.

Fig. 6. Elemental EDS pattern on brown-reddish (a) water-side wall of tube sheet and (b) external-side of the cover wall surface.

In addition, EDS testing was performed on the weldment and base metal. On the other hand, both EDS patterns are similar because all of the essential elements in the studied area are identical. Because of this, there is no evidence for the presence of the galvanic corrosion effect. Consequently, it has been ruled out that a corrosion-related fault caused the leakage of the boiler economizer.

An optical emission spectrometer (OES) was used to establish that the material used in the economizer boiler was SUS304. The results of the tests, which are presented in Table 1, demonstrate that all samples are compliant with SUS304 grade stainless steel. On the other hand, the Cr and Ni levels are somewhat lower than the specified composition range of SUS304. In cases involving corrosion-related failures, the stainless steel's lack of Ni and Cr may be the primary cause. Therefore, asset owners should use more caution throughout the acquisition process. In addition, inspections should be performed throughout the commissioning phase. However, this study was not deemed a significant problem since the primary cause of failure was not corrosion-related. The other potential explanation for the slight reduction in Cr and Ni content is the depletion of their atoms, which are utilized especially on the surface to form a passive layer that can withstand the oxidation process induced by the operating conditions.
Table 1. Chemical composition of boiler economizer component

| Element | SUS304 | Analysis |
|---------|--------|----------|
|         | Tube Sheet | Tube | Cover |
| C       | 0.08 max. | 0.029 | 0.032 | 0.044 |
| Si      | 1.00 max. | 0.365 | 0.405 | 0.385 |
| Mn      | 2.00 max. | 1.650 | 1.780 | 1.730 |
| P       | 0.045 max. | 0.032 | 0.030 | 0.032 |
| S       | 0.030 max. | 0.007 | 0.008 | 0.008 |
| Ni      | 8.00–10.50 | 7.949 | 8.649 | 8.001 |
| Cr      | 18.00–20.00 | 17.91 | 18.77 | 17.97 |
| Others  | 72.06 | 70.33 | 71.83 |

There are many sections in the construction of a boiler economizer that need welding. Accordingly, the failure of an economizer as a result of welding imperfections is not unexpected. In this investigation, it was discovered that the weld crater is the primary reason, which is also responsible for causing residual welding stress, which in turn causes cracks to form around the welding region. The weld crater happens after the welding process, which is typically found near the end of the welding bead.

The most common reason for a weld crater is because the welding process was stopped prematurely, resulting in the rapid solidification of a considerable weld pool. Perhaps, this fault developed as a result of insufficient welder experience or improper welding skills. Premature termination during the welding process does not allow enough time for the molten pool to fill the void. As a result, they become a point of weakness inside a weld. The development of a crater at the end of a weld, on the other hand, makes it even weaker. Therefore, cracks occur due to the weld pool's lack of volume to withstand the stress caused by shrinkage.

The weld crater shows that there is a disparity in the cooling rate of metal weldment during solidification. When an object is cooled from a high temperature (e.g., after welding), there is often a significant variation in the rate of cooling throughout the body. The disparity in cooling rates between the object's surface and inside causes localized differences in thermal contraction. The differing thermal contractions develop non-uniform stresses. When cooling occurs, the surface cools more rapidly, compressing the hot material in the center. As the material in the center tries to cool, it is constrained by the colder outer material. As a result, the inner part of the component will retain tensile tension, whereas the outside portion will retain compressive stress. For this reason, any area close to the weld crater is prone to experience residual stress. The residual stress causes cracking due to the weld crater will not always manifest itself immediately after welding. Instead, cracks can form over time as the weld is subjected to stress from tension, twisting, and so on. Thus, they can manifest themselves within a day, two weeks, three months, or even years.

The removal of the stop or the use of a specific welding technique may help to avoid crater defects as a preventative measure. It is possible to remove the stop by inserting a run-off tag in the butt joints. The weld crater may also be eliminated by grinding off the stop before proceeding with the next electrode or depositing the following weld run. Depending on the welding technique, it may be accomplished by gradually decreasing the welding current to decrease the weld pool size, using appropriate 'crater filler' devices, or injecting filler to compensate for the shrinking of the weld pool. Additionally, failures such as the one in this instance may be avoided by using the appropriate post-weld heat treatment (PWHT) or stress release to decrease the welding stress after the weld has been completed.
Furthermore, reducing sulphur content in an economizer's combustion and post-combustion phases is possible to reduce rusting occurring on the economizer's outer cover.

4 Conclusion

Improper welding procedure leads to crater defects, creating residual welding stress and causes cracks near the welding area. However, the condensed or flue gas containing sulphur caused rusting on the outer wall cover of the boiler economizer is not an issue since it does not produce corrosion-related severe failures or even metal imperfections. Therefore, SUS304 stainless steel as an economizer material is also not regarded as a cause of failure.

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References

1. F. A. Rahman, M. M. A. Aziz, R. Saidur & W. A. W. A. Bakar. AIP Conf. Proc. 2030, 1, 020291 (2018)
2. C. Subramanian, Eng. Fail. Anal, 115, 104643 (2020)
3. C. A. Duarte, E. Espejo & J. C. Martinez, Eng. Fail. Anal. 79, 704 (2017)
4. U. Pal, K. Kishore, S. Mukhopadhyay, G. Mukhopadhyay, & S. Bhattacharya, Eng. Fail. Anal, 104, 1203 (2019)
5. N. Mohamed, F. Byron, & C. A. Imbert, 1, 35. (2021).
6. Saragi Sitio, I. S., & Pramono, A. W. Doc. Dissertation, Inst. Tekn. PLN (2020)
7. D Ghosh, H Roy, Chidambaram Subramanian, J. Fail. Anal. Prev. 3, 21, 1 (2021)
8. C. R. Corleto & G. R. Argade, C. St. Eng. Fail. Anal. 9, 27 (2017)