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Investigation of failure of steel steam generating evaporator tube involving delamination defects and corrosion

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ABSTRACT

A low carbon steel tube burst at a coal powered power station (Orot-Rabin station, Hadera-Israel). The tube was composed of material specified to ASTM A210M-02 Gr. A1. The bursting of the tube caused a steam/water mix to escape through a hole during initial unit activation after maintenance repairs. The tube is a diagonal ribbed steam-generating tube, mainly used as a physical support for a superheater coil assembly. During internal visual inspection using a borescope, it was seen that a whole layer of metal had partially detached from the area around the hole, causing the tube wall to thin considerably prior to failure. Moreover, it was seen that the same area had undergone corrosion at an advanced stage. Optical metallography revealed that the metal layer had detached from the tube's internal surface due to a wide and thick two-dimensional delamination defect present beneath the internal surface, and that a large amount of copper was present near the detached layer's edge. Scanning Electron microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) verified the existence of an abnormal concentration of copper and zinc at the same location. This led to the final conclusion that the hole in the tube had formed due to a combination of a wide delamination defect left over from production, and severe galvanic corrosion enabling the defect's exposure and delamination, eventually causing wall thinning and failure.

1. Introduction

Steels are used as common and widespread engineering alloys employed in many branches of industry such as food, petrochemicals, medicine, transport and power industries [1–4]. Particularly, they are a long time 'work horse' and prime material for the conventional power generation industry [5–8]. Failures in fossil fuel power stations involving steel are very common and include failure modes such as creep in boiler tubes [9], hot corrosion phenomena [6], high-temperature overload [10], fatigue [11], and other failure modes also involving other metals in adjacent sub-systems [12]. These failures occur due to incorrect welding processes, errors in plant operation, lack of timely maintenance, natural material deterioration and other causes [11].

Another important cause of failure is the presence of production defects, and their influence on the mode of failure. Metallurgical defects left over from production or installation have been known to be involved in a myriad of damage mechanisms and failures such as dent and gouge defects [13], inclusions and carbide segregation causing embrittlement [14], casting discontinuities such as porosity enabling cracks and stress concentration [15] to give a few examples.

The following work presents the failure of a ribbed diagonal steam-generating evaporator tube (OD: 63 mm, wall thickness: 6 mm, working hours: ~200,000), also used as a physical support for a superheater coil assembly in a boiler (~140 atm, 500–550 °C). Galvanic corrosion caused by the presence of copper, caused the gradual exposure of a production-induced delamination defect near

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the internal surface, and the subsequent detachment of a metal layer into the tube interior. Thereafter, the wall thickness thinned dramatically culminating in a steam/water mix bursting out through a hole. Advanced corrosion could be observed visually, while the presence of a wide delamination defect with its unique characteristics was observed via optical metallography. Through the latter method it was also possible to observe an abnormal amount of copper and zinc at the area where the detached layer's edge and the tube connected. The presence of copper and zinc was confirmed via semi-quantitative SEM and EDS mapping while optical emission spectroscopy (OES) was employed to determine the elemental composition of the material.

The above evidence finally led to the conclusion that the failure had occurred due to the combination of advanced hot galvanic corrosion and detachment due to a delamination defect, eventually leading to wall thinning and steam leakage. The tube exclusively contains a steam/water mix, is situated within the boiler and subject to the conditions within it. The steam generating tube is referred to throughout the remainder of the report as the 'tube'.

2. Experimental methods

Macro images were taken using digital photography and internal images of the tube were taken with a borescope. Stereoscopic images were taken with a binocular microscope equipped with a digital camera. Optical emission spectroscopy measurements were conducted with a spectrometer according to the ASTM E1476-97 standard [16]. (High Resolution) HR-SEM images were performed with a microscope equipped with an EDS detector. Specimens for optical metallography were prepared according to the ASTM A262-02a [17] standard and were observed in an optical microscope equipped with a digital camera.

3. Failure analysis

3.1. Visual inspection

An image of the tube as received from the power station including a close view of the hole is presented in Fig. 1.

Visual examination revealed combustion and ash deposits typical of coal fired boilers on the tube's outer surface. Around the hole it is possible to observe radial marks caused by the steam burst, it is suggested the deep red hue around the edge of the hole constitutes evidence of hot corrosion (Figs. 1–2). The tube was sectioned and the ribbed inner surface near the hole was revealed, as presented in Fig. 2. It is observable that a whole layer of metal had detached from the surface at the area where the hole had formed, a sketch of the cross section is presented in Fig. 3 (working parameters supplied by power station staff). By observing that the hole exists on the tube wall but is absent from the detached layer, it is discernible that the detachment had occurred prior to the hole formation. The substantial wall thinning due to the detachment created a situation where the remaining wall thickness could not withstand the working pressure and temperature, leading to accelerated wall thinning until it breached. Yellowish deposits can be observed near and around the peeled area. The yellow deposit layer's abrupt cut-off at the surface left over from the detachment shows that the layer existed on the surface before the detachment event (Fig. 2). Evidence of hot corrosion in the form of a deep red hue can be seen near the hole on the internal surface of the tube (Fig. 2), as also seen from the external surface in Fig. 1. Due to the limited radius of the red corroded surface, it is strongly suggested that this corrosion, and possibly simultaneous erosion, occurred near the time of breach, and that at the same time, the hole area experienced temperatures much higher than the rest of the tube. It is suggested that these high temperatures were both due to friction of gas flow and very high heat transfer from the exterior prior to and during the burst, when wall thickness became very thin (in the immediate vicinity of the hole). This is evident by the absence of deep-red corrosion products beyond 2–3 mm from the hole, apart for limited superficial corrosion common in evaporator tubes. The wall thickness at the hole is ~300 μm compared to 6 mm, and the outer surface has remained intact apart for the hole itself.

Curiously, apart for the corrosion evidence around the hole (Fig. 4a), corrosion products were also observed at a conspicuous spot on the inner surface at exactly 180° to the hole (Fig. 4b). It is believed that the spot appeared as a consequence of the hole in the tube.

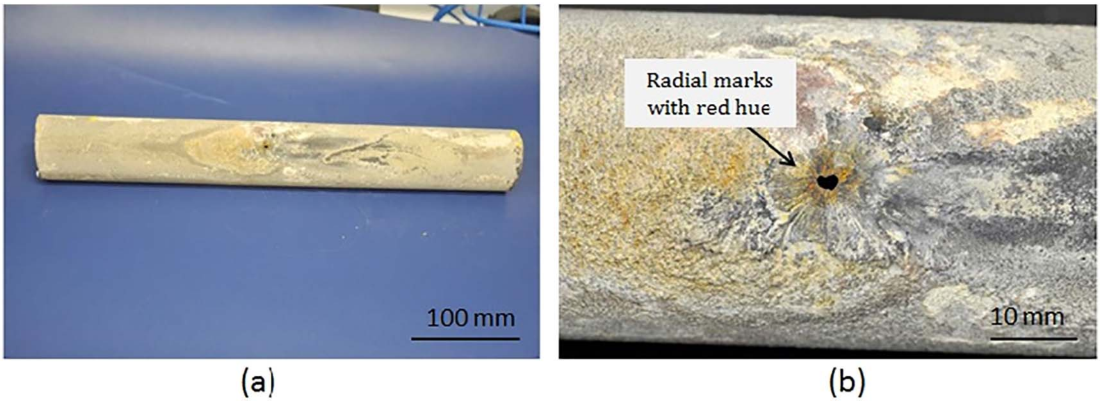

Fig. 1. (a) Showing the tube as received from the field (b) a close view of the hole.