Engineering Failure Analysis 45 (2014) 398–405

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

Review

Root cause analysis of stress corrosion at tube-to-tubesheet joints of a waste heat boiler

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ARTICLE INFO

Article history:
Received 16 February 2014
Received in revised form 7 July 2014
Accepted 15 July 2014
Available online 23 July 2014

Keywords:
Expansion pressure
Tube-to-tubesheet joint
Waste heat boilers
SCC of tubes

ABSTRACT

Leakage at the tube-to-tubesheet joints occurred in a waste heat boiler. The mode and the root cause of the failure were investigated by chemical composition analysis of the tube material, metallographic structure and crack observation, and corrosion product analysis of the damaged tubes, as well as the operation condition examination of the waste heat boiler. Results revealed that failure of the tubes occurred due to the stress corrosion cracking (SCC), which was caused by tensile stress and chloride-buildup in the narrow and long gap between the tube and tubesheet hole. The gap formation was further analyzed by comparison of the minimum expansion pressure from the common formula provided by the manufacturer, with that from finite element method computations. It is found that the minimum expansion pressure used in manufacture is small and cannot eliminate the initial gap. Meanwhile, the enrichment of chloride in the gap was briefly discussed.

1. Introduction

Shell-tube heat exchangers are widely used in chemical, petroleum, medicine and nuclear industries. The connection of the tube-to-tubesheet is a critical element of shell-tube heat exchangers. This joint is made by either expansion, welding or a combination of the two processes [1]. Many failure cases of waste heat boilers occurred at the joints. Stress corrosion cracking is a common failure mode in waste heat boilers, which is easily caused by the combined action of tensile stress and a specific corrosive medium. Tensile stresses may be from the operating pressure and residual stresses due to expanding or welding. Studies have shown that the residual stresses play an important role to the SCC [2,3].

In some failure cases, stress corrosion cracks appeared on the external surface of the tubes although the chloride content was significantly low in the medium. It was considered that SCC occurred due to the concentration of chlorides in the gap between the tube and tubesheet hole [4]. The chloride content could reach as high as 2410 ppm in the gap up from the low value of 5.8 ppm [5]. Although expansion was used to eliminate the gap between the joints, stress corrosion cracking and crevice corrosion could not be avoided [6,7]. The formation cause of the gap is not clear when expansion is applied. This will be discussed in this paper.

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http://dx.doi.org/10.1016/j.engfailanal.2014.07.013
1350-6307/

We will investigate the root cause of a water-gas waste heat boiler failure. Both the traditional formula and the FEM were used to calculate the expansion pressure, aiming to provide an appropriate expansion pressure for eliminating the gap between the tube and tubesheet hole. The mechanism of chloride-buildup in the gap was also analyzed.

2. Description of a failure case

A waste heat boiler is used in a methanol plant. The operating medium in shell side is superheated steam and water. All the tubes are completely filled with water-gas including H_2, CO, CO_2, H_2S, NH_3, and H_2O. The highest operating pressure and temperature of the tube side are 6.28 MPa and 241 °C, respectively. The highest operating pressure and temperature of the shell side are 3.4 MPa and 242 °C, respectively. The tube is made of Type 0Cr18Ni10Ti austenitic stainless steel. The tubesheet is manufactured from a type of low alloy steel, 20 MnMo. This joint of the tube-to-tubesheet is made by the combination of strength welding and sealing expansion. In December 2012, the indication of leakage in some tubes was observed.

3. Failure analysis and results

According to the site survey, the leakage was confined to the region within the joint between the tube and tubesheet, as shown in Fig. 1(a). No crack was found on the inner surface of the tube at the rolled end with the naked eye. Cracks were observed after being penetrant inspected and polished, as shown in Fig. 1(b). The width of the cracks increases with the depth increasing.

3.1. Material composition

The chemical composition of the tube material is shown in Table 1, which is consistent with that of 0Cr18Ni10Ti, as specified by GB 13296-2007 [8].

3.2. Crack appearance

The outer surface of the failed tube was polished using sand paper, then the visible cracks appeared. Samples with cracks were cut and prepared for the further observation. Electron Probe Micro analyser examination reveals a main axial crack and branching of the main crack can be seen, as shown in Fig. 2(a). In the aqua regia etched condition, the branching crack and transgranular crack are observed, as shown in Fig. 2(b).

The corrosion products in the crack gap were analyzed using an Electron Probe Micro analyser. The results indicate that there are sulfide, chlorine, oxygen and calcium in addition to the base metal elements, as shown in Fig. 3 and Table 2.

3.3. Optical metallography

For comparison, one sample was taken from the cracked region of the tube and the other from the un-attacked part. After being polished and etched in the aqua regia, the microstructure and morphology of the two samples were examined by optical microscopy. Fig. 4 shows the microstructure photo at the and away from the cracked region. The microstructure was an equiaxed austenitic structure with fine grain size, and the twin was observed at the same time. The grain boundaries remained intact.

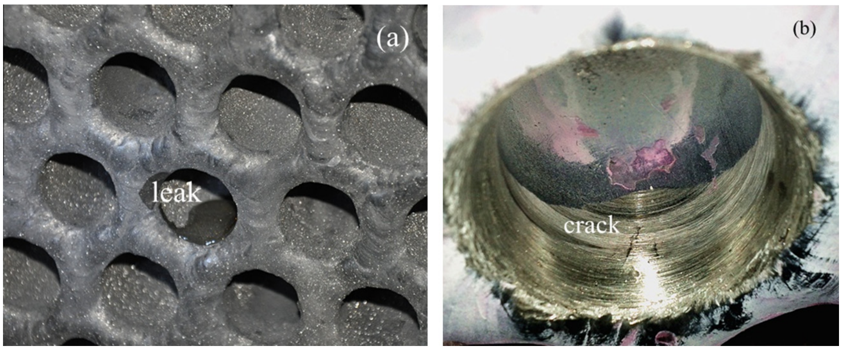

Fig. 1. Leakage position and crack appearance on the tube of the water-gas waste heat boiler. (a) leakage position and (b) crack appearance.