Engineering Failure Analysis 79 (2017) 704–713

Contents lists available at ScienceDirect

Engineering Failure Analysis

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

Failure analysis of the wall tubes of a water-tube boiler

Camilo A. Duarte*, Edgar Espejo, Juan Carlos Martinez

Department of Mechanical & Mechatronics Engineering, Universidad Nacional de Colombia, Bogota, Colombia

ARTICLE INFO

Keywords:
Boiler tube
Stress corrosion cracking (SCC)
Pitting corrosion
Residual stress
Finite element analysis

ABSTRACT

An industrial case history of the failure of the evaporator (water wall) tubes of a water-tube boiler is presented in this study. After two years in service, a leak was detected in one of the tubes over its bent section with pitting corrosion on its internal surface. Later on, the same symptoms were discovered in other tubes of the same boiler, and several tubes were extracted for failure analysis. On the basis of visual inspection, chemical analysis, microstructural examination, hardness measurements, and residual stress measurements via X-ray diffraction (XRD), the failure mechanism of the tubes was identified as stress corrosion cracking (SCC). In this paper, the results obtained from the experimental analysis are summarized, and finite element (FE) models are used to predict the residual stress due to the bending of the tube and the operational stress at the moment of failure. It was found that tensile residual stress from an inadequate stress relief treatment prior to service and high concentration of dissolved oxygen in the feed water were the main reasons for the premature failure of the boiler tubes by SCC.

1. Introduction

In water-tube boilers, the water that circulates through the boiler tubes is externally heated by hot gases coming from the furnace resulting in generation of superheated steam. Since these machines operate at high temperature, at high pressure, and in abrasive environments, boiler tubes often suffer from a variety of failure mechanisms, such as overheating [1,2], pitting corrosion [3,4], creep [5], erosion [6], thermal fatigue [7], corrosion fatigue [8], and stress corrosion cracking (SCC) [9]. In particular, SCC has been shown to be one of the most important factors that limit the performance of boilers [6].

Stress corrosion cracking (SCC) occurs as the result of three conditions: (a) high tensile stress, either applied (internal pressure or bending) or residual stress induced during manufacturing or welding, (b) operation in a corrosive environment, and (c) a susceptible material, for instance, with the inadequate mechanical properties for the application. In boiler tubes made of carbon steel, the most common corrodents associated with this type of failure are oxygen and sodium hydroxide [5]. Furthermore, factors such as temperature, pH, pressure, dissolved oxygen in feed water, and improper operational conditions may affect the probability of the occurrence of this failure mechanism. Particularly, in boiler tubes made of carbon steel, it is essential to maintain an alkaline environment in order to keep the magnetite layer in place and to avoid waterside corrosion.

The case under study in this paper corresponds to the history of failure of the evaporator tubes of a water-tube boiler, part of a coal-fired thermoelectric power plant, analyzed from 2001 to 2006 (see Fig. 1). The boiler fed a turbine of 165 MW with steam at a temperature of 500 °C and a pressure of 150 bars (15 MPa), and it had a capacity of 486,000 kg/h. The tubes of the evaporator in the failure zone were made of seamless steel ASTM SA210 grade A1, hot-finished, and had a nominal outer diameter of 57 mm, wall thickness of 5.4 mm. and bend radius of 127.0 mm. They were manufactured by cold bending and stress relief heat treatment (Fig. 2a). According to the specifications, the boiler was designed based on B31.1 ASME code [10], which recommends maximum

* Corresponding author at: Universidad Nacional de Colombia, Ciudad Universitaria, Secretaria 2do piso, Edificio 407, Bogotá, Colombia.
E-mail addresses: caduartec@unal.edu.co (C.A. Duarte), eespejom@unal.edu.co (E. Espejo), jcmartinezro@unal.edu.co (J.C. Martinez).

http://dx.doi.org/10.1016/j.engfailanal.2017.05.032
Received 27 May 2016; Received in revised form 14 January 2017; Accepted 4 May 2017
Available online 05 May 2017
1350-6307/

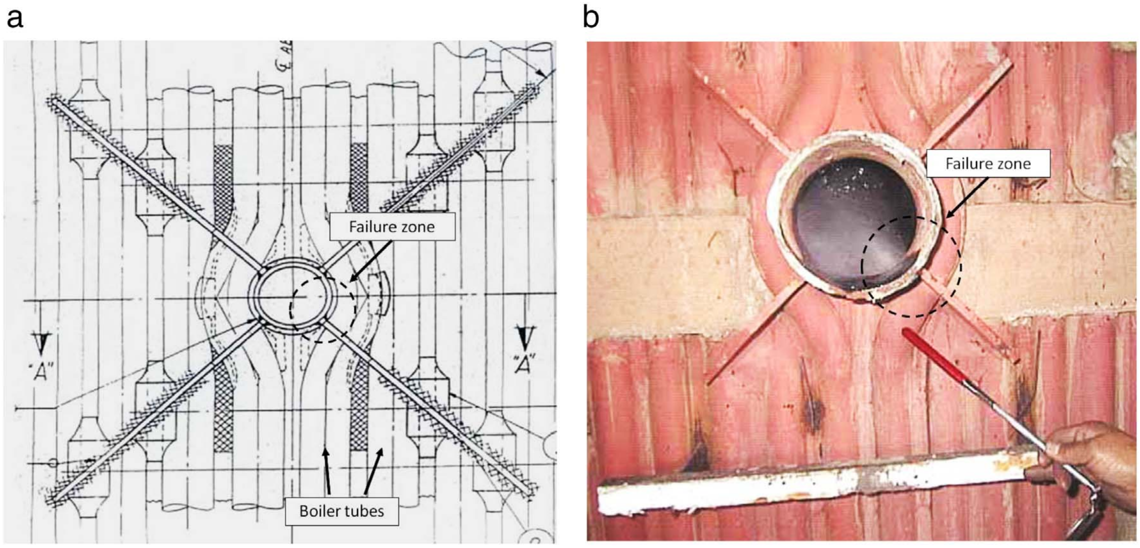

Fig. 1. (a) Schematic drawing of the water-tube boiler showing failure zone and (b) macrograph of the water-tube boiler showing crack zone in the wall tube.

operating parameters of a temperature of 510 °C, tensile stress of 102 MPa, and dissolved oxygen of 7 ppb.

The boiler started to operate in 1999. In 2001, one of the boiler tubes presented a leak in its bent section. Over this area, a crack at an approximate angle of 45° to the tube axis was identified, as well as pitting corrosion on the inner surface of the tube; the corrosion pits were concentrated in the bent section of the tubes (see Fig. 2b and c). Six months later, the same symptoms were exhibited by another tube. At the failure site, the operating parameters were a pressure of 150 bars and a temperature of 350 °C, and the operating medium was saturated steam (see Table 1). In 2006 all remaining bent tubes were removed (eight), showing corrosion pitting on their inner surface.

2. Experimental procedure

Several sections of the boiler tubes, extracted from both the straight and bent sections of the boiler wall-tubes, were brought for failure investigation. Background information related to the operational conditions and the material of the tubes was provided by the company that operates the coal-fired thermoelectric power plant. So as to identify the root cause, four samples were cut from different tubes and their chemical composition was obtained. Also, two tubes from the bent and straight sections of the evaporator were selected randomly and four samples were cut from each tube. These samples were used for corrosion product analysis, metallographic analysis, hardness measurements, and residual stress measurements by XRD. For microstructural examination, smaller specimens were cut using an abrasive cutter, polished using standard metallographic techniques, and etched with 3% Nital reagent.

3. Results

3.1. Visual and microscopic inspection

Visual examination of the internal surface of the tubes revealed corrosion pitting, particularly a large concentration of corrosion pits in the bent section of the tube (Fig. 2c and d). The pits are deep and elliptical (Figs. 2d and 3c). Cavitation was discarded since there is no fluid pressure drop along the tube, and the morphology of the pits does not correspond to this failure mechanics (wide and shallow pits). Furthermore, some of the pits showed characteristics of tuberculation, which suggests that they were active and growing during normal operation of the boiler. Inspection of the damaged area revealed a crack at an approximate angle of 45° to the tube axis (Fig. 2a and b). The crack originated on the inner surface of the tube and grew across the tube wall until it reached the other surface. The micrographs revealed the presence of corrosion pitting and intergranular cracking (Fig. 3). The average measured outer diameter of the tubes was 56.7 mm and the thickness was 5.8 mm, indicating a low rate of uniform corrosion.

3.2. Chemical analysis

The chemical analysis of the four specimens sampled from the failed boiler tubes was carried out using optical emission spectroscopy (OES) on Baird Spectrovac model DV-4 spectrometer. According to the manufacturing specification, the boiler tubes are made of ASTM SA210 grade A1 steel. A summary of the results obtained for each sample is shown in Table 2. The material meets the chemical composition requirements as specified by ASTM [11].