Applied Surface Science 258 (2012) 6512–6526

Contents lists available at SciVerse ScienceDirect

Applied Surface Science

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

Microbiologically influenced corrosion (MIC) in stainless steel heat exchanger

E. Huttunen-Saarivirta[a,*], M. Honkanen[a], T. Lepistö[a], V.-T. Kuokkala[a], L. Koivisto[b], C.-G. Berg[c]

[a] *Laboratory of Materials Characterization, Department of Materials Science, Tampere University of Technology, P.O.B. 589, FI-33101 Tampere, Finland*
[b] *Andritz Oy, Recovery and Power Division, P.O. Box 184, FI-78201 Varkaus, Finland*
[c] *Andritz Pulp & Paper, Tammasaarenkatu 1, FI-00180 Helsinki, Finland*

ARTICLE INFO

Article history:
Received 14 February 2012
Received in revised form 12 March 2012
Accepted 13 March 2012
Available online 21 March 2012

Keywords:
Stainless steel
Microbiological corrosion
Passivation
Austenite
Ferrite

ABSTRACT

Corrosion attack in the form of corrosion product tubercles was observed in an AISI 304 (EN 1.4301) stainless steel heat exchanger only after 36 months of service. Failure analyses revealed that in one of the attacked areas corrosion had penetrated the entire wall thickness of 6.2 mm, but in most of the cases it reached the depth of 2–4 mm. In this paper, we report the results from a thorough microstructural characterization of the corroded heat exchanger carried out with optical microscopy (OM), scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), transmission electron microscopy (TEM) and X-ray diffractometry (XRD).

Microstructural studies by OM, SEM and XRD revealed a two-phase structure of austenite and ferrite in the bulk material, as well as the preferential attack of the ferrite phase. SEM surface studies disclosed bacteria in and close to the attacked areas. Cross-sectional SEM examinations showed the distribution and composition of corrosion products within and underneath the tubercles. TEM and XRD studies gave information about the amorphous and/or nanocrystalline nature of some of the formed corrosion products. These results are discussed in this paper and, based on them, the main corrosion mechanism for the observed attack is suggested. Further, explanations for the propagation of corrosion along the ferrite phase are presented.

1. Introduction

Heat exchangers are systems that are used to transfer thermal energy between two or more fluids, between a solid surface and a fluid or between solid particles and a fluid, at different temperatures and in contact. Typical applications involve heating or cooling of a fluid stream of concern and evaporation or condensation of single- or multicomponent fluid streams. Classification of heat exchangers may be carried out in several ways, such as according to their construction, including, for example, plate-type, tubular, extended surface and regenerative heat exchangers. Tubular heat exchangers find use in many industrial applications due to their availability for a wide range of capacities and operation conditions, such as from high vacuums to ultra-high pressures (over 100 MPa) and from cryogenic to high temperatures (about 1100 °C). To enable desired thermal performance, the heat transfer surfaces have to meet independently of the heat exchanger construction or design, tight criteria in terms of dimensions, surface quality, flow conditions and pressures [1,2]. Accumulation of material or deposits, such as corrosion products, biological growth and sediments, on the surfaces of the heat exchanger system is essentially undesirable, because these increase frictional resistance and reduce heat transfer efficiency [3]. However, microbiological growth in systems containing liquid streams in the temperature range from 0 to 90 °C, and in particular from 20 to 50 °C, is not unusual. When present, microbial growth occurs as a formation of a biofilm on the surfaces, thereby possibly contributing to other surface processes, such as corrosion [1–3].

Microbiologically influenced corrosion (MIC) is not an actual form of corrosion but a process which involves micro-organisms that may initiate or otherwise contribute to the propagation of corrosion, typically accelerating the existing corrosion form [4,5]. Micro-organisms, i.e., bacteria, algae and fungi, which exist practically in all natural aqueous environments have a tendency to attach to and grow on the surfaces of structural materials. They create and use polysaccharides and other exopolymers to bind themselves to the surfaces; these exopolymers together with the micro-organisms form a complex microbiological matrix called biofilm [6,7], as mentioned above. The biofilm may then change the local environment on the surface by influencing the access of electrolyte on the surface or through metabolic reactions [5,6]. On this basis, several environmental parameters, such as pH, dissolved oxygen and concentration of chemical species, may under the biofilm be quite different from that in the bulk electrolyte [4]. Most bacteria that have been implicated in corrosion thrive and grow best in the temperature range from 15 to 45 °C and in the pH range from 6 to 8.

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[*] Corresponding author. Tel.: +358 40 8490134, fax: +358 40 1981233.
E-mail address: elina.huttunen-saarivirta@tut.fi (E. Huttunen-Saarivirta).

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doi:10.1016/j.apsusc.2012.03.068

Table 1
Chemical composition, in wt%, of the heat exchanger bulk material, obtained using optical emission spectroscopy.

	C	Si	Mn	P	S	Cu	Al	Cr	Mo	Ni	V	Ti	Nb	Co	W	Fe
Bulk material	0.013	0.334	1.726	0.002	0.002	0.252	0.003	17.03	0.338	8.72	0.051	<0.005	0.020	0.140	0.029	71.33

In terms of oxygen content of the environment, microbes may typically be classified into three categories: aerobic species that require oxygen for their metabolism, anaerobic species that live only in the absence of oxygen and facultative bacteria that can grow in either environment although they usually prefer aerobic conditions [4,8].

In typical studies of microbiologically influenced corrosion, for example Refs. [9–16], a specimen of a known metal or alloy is immersed in a specific electrolyte where a particular bacterium species is being cultivated under controlled conditions. The resulting changes in the specimen are followed by electrochemical measurements and microstructural studies, with the corrosion mechanism being of key interest. Although this is a fruitful and essentially reproducible approach, microbiological activity and its consequences under controlled laboratory conditions may be quite different from those in real operating or process environments. For example, corrosion and degradation processes under natural conditions are commonly associated with a mixed population of micro-organisms [3]. In this study, we examine microbiologically influenced corrosion by taking a practical approach, i.e., by analyzing an observed corrosion attack of a stainless steel heat exchanger. In this paper, we report thorough microstructural investigations of the heat exchanger bulk material and the corrosion product tubercles formed on the surfaces, which enable discussion of the mechanism and reasons for the corrosion attack. Indeed, the observations of the bacteria are also documented to confirm that micro-organisms are really involved. Besides the case-study approach, the novelty of the paper lies in the unique connection between the corrosion mechanism and the heat exchanger material microstructure.

2. Failure analysis

Tubercles of a corrosion product were detected only after 36 months of service on the surface of a horizontal multi-pass shell-and-tube type heat exchanger in the tube-side, i.e., in contact with fresh water originating from a cooling tower. The inlet temperature of the water was 45 °C, whereas at the outlet end the water temperature was about 75 °C. The heat exchanger was made of stainless steel of the type 304, EN 1.4301, with material analysis given in Table 1. The specimens for the present investigation included samples with evident corrosion product tubercles on the surface (Fig. 1a–b) and samples without apparent tubercles. The specimens were cut from neighbouring areas of the damaged heat exchanger exposed to similar operating conditions. After cutting, a detailed visual examination revealed that in one of the specimens with corrosion tubercles corrosion damage had penetrated the entire wall thickness, 6.2 mm. However, in most of the cases, corrosion had reached only the depth of 2–4 mm. Tubercles occurred randomly on the surface of the heat exchanger shell, i.e., both on the uniform areas of the surface as well as on the corner welds.

The phase structure of the heat exchanger material was determined by X-ray diffractometry (XRD) using a polished specimen, Siemens D-500 X-ray diffractometer and CuKα radiation. Cross-sectional specimens were prepared from the areas with and without corrosion product tubercles by conventional metallographic specimen preparation methods. Microstructure of the bulk material was studied using both types of specimens etched with V2A, an optical microscope (OM) Nikon Eclipse MA100 and a field emission scanning electron microscope (FE-SEM) Zeiss ULTRA-plus, equipped with secondary electron (SE) and angular selective backscattered electron (AsB) detectors and an energy dispersive spectrometer (EDS) INCA Energy 350 with an INCAx-act detector. A HKL Premium-F Channel electron back-scattered diffraction (EBSD) system with Nordlys F400 detector, attached to FE-SEM, was used for local phase identification in the specimens that were electrolytically polished using Struers Lecropol 5 device and Struers A2 electrolyte. In addition to microstructural characterization, hardness measurements were conducted for the bulk material of both types of specimens using a Vickers diamond indenter and 5 kg load on a Duramin A-300 device. Hardness measurements were performed on three areas: near the surface, at the center and near the bottom. Five readings were taken at each location.

The surface of the corroded area, shown in Fig. 1, was studied with stereomicroscope Leica MZ 7.5 from the top-view and with scanning electron microscope (SEM) Philips XL-30. The corrosion product tubercles were examined by using sputter-carbonized cross-sectional specimens and the FE-SEM. In addition, some of the corrosion product was scraped off from the surface, crushed between two laboratory glasses and characterized by XRD and transmission electron microscopy (TEM). XRD measurements were carried out as described above, except for using powder specimens. TEM studies were performed by employing a Jeol JEM 2010 microscope equipped with a Noran Vantage EDS detector, and a copper grid with holey carbon film to sustain the corrosion product powder.

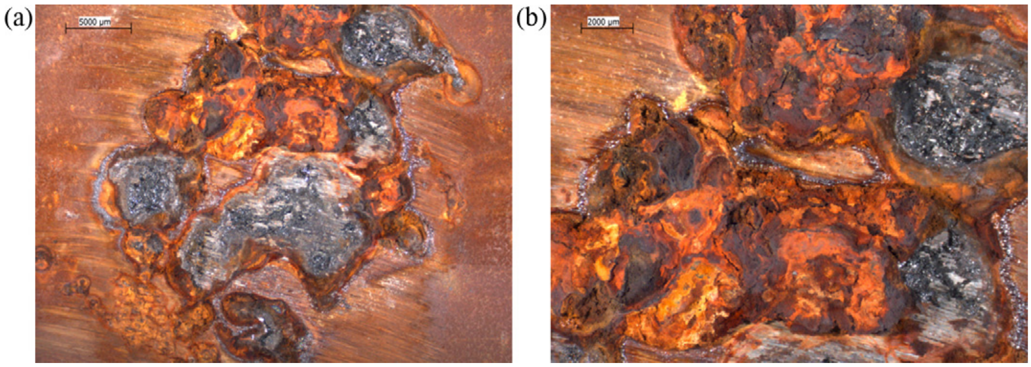

Fig. 1. Stereomicroscopy images of the corrosion product tubercles on the heat exchanger surface. (a) A general view of the tubercle area. (b) A detailed view of the tubercle.