



ELSEVIER

Contents lists available at ScienceDirect

Case Studies in Engineering Failure Analysis

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

Case study

Stress corrosion cracking in Type.316 plates of a heat exchanger

S.H. Khodamorad^{a,*}, N. Alinezhad^a, D. Haghshenas Fatmehsari^b, K. Ghahtan^a^a Inspection Department of Jam Petrochemical Complex, Asalouyeh, Iran^b Amirkabir University of Technology, Department of Mining and Metallurgical Engineering, Tehran, Iran

ARTICLE INFO

Article history:

Received 25 November 2015

Received in revised form 25 February 2016

Accepted 7 March 2016

Available online 12 March 2016

Keywords:

SCC

Chloride build-up

Pitting

Plate heat exchanger

ABSTRACT

In Jam petrochemical complex (JPC), Iran, the plates (ASTM A.240 Type.316) of some heat exchangers have been damaged due to the occurrence of cracks at the sitting place of gaskets. A comprehensive failure analysis including the chemical analysis, visual inspection, optical microscopy and scanning electron microscopy (SEM) of the cracks spread over the plates together with the energy dispersive X-ray spectroscopy (EDS) of the corrosion products and the measurement of chloride and sulfide ions content of the process water were employed for the examination of the failure mode and its causes. The obtained results indicate the building-up of the chloride and sulfide ions at the crevices between plates and gaskets at high temperature leads to stress cracking corrosion (SCC) of the plates. Moreover, the simultaneous presence of chloride and sulfide in the media hastens the SCC failure in the heat exchanger plates.

© 2016 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

1. Introduction

Stress corrosion cracking (SCC) is cracking due to a process involving conjoint corrosion and straining of a metal due to residual or applied stresses. SCC is known as an insidious form of corrosion failure and it results in a significant drop in the mechanical strength only with little metal loss. Another important point is that although this failure cannot be recognized by casual inspection, it can lead to a catastrophic damage of components and structures such as the rupture of high-pressure gas transmission pipes, the explosion of boilers and the destruction of power stations and oil refineries.

In phenomenological viewpoint, the occurrence of SCC depends on three simultaneous requirements; a susceptible material, an environment that causes SCC for that material, and sufficient tensile stress to induce SCC. Three principal mechanisms of SCC are active path dissolution (accelerated corrosion along a path of higher than normal corrosion susceptibility such as the grain boundary), hydrogen embrittlement and film-induced cleavage. However, SCC is an avoidable process by preventing the specific combinations of metal and environment that are subject to the problem.

Heat exchangers are common equipments in many industries employed for the cooling/heating purposes. The plate heat exchanger (PHE) or plate and frame heat exchanger is a type of heat exchangers that comprises of the special metal plates and sealing polymeric gaskets; when two fluids with different temperatures pass over two opposite sides of the plates, the heat transfers from the hot side to the cold side. Excellent heat transfer characteristics, easy maintenance and fast

* Corresponding author at: P.O. Box 14155-6591, Asalouyeh, Iran. Tel.: +98 9123541962.

E-mail address: hkhodamorad@gmail.com (S.H. Khodamorad).

modification are the advantages of this type of heat exchangers which make them a widely used and important part of many industries such as petrochemical complexes [1]. Austenitic stainless steels are widely used in manufacturing of the special plates for PHE. The main benefit of the stainless steels is the corrosion resistivity. However, as previously mentioned, they are susceptible to local corrosion like pitting corrosion and stress corrosion cracking (SCC) [2–4]. Cooperation of stress and specific media such as the chloride or sulfide containing media is mandatory for SCC of susceptible materials. The simultaneous presence of mechanical stress and chloride or sulfide ions in environment accelerates the corrosion failure of metal.

A survey of previous literature on prevention of SCC failure provides some clues about the important factors in such systems. For example, Orlikowsky and Krakowiak [5] studied the SCC failure of an AISI 304 stainless steel tank containing hot water (70–80 °C) containing 55–100 mg/dm³ chloride ions. They reported the causes of SCC as the bending of unclamped surge pipeline, hydrostatic pressure of water and buckling forces of tank as the origin of stress. Moreover, Yongde et al. [6] evaluated the failure of a 304 stainless steel tube in gas analyzer and they found that the presence of chloride and sulfide in the ventilating pipe and the residual stresses of manufacturing together with the airflow pressure on the pipe are responsible for the corrosion failure.

In Jam petrochemical complex (JPC), Iran, the plates of some heat exchangers have been damaged due to the occurrence of cracks at the sitting place of gaskets. The heat exchangers have been in service since 2008. They are placed in a wet environment (with a humidity of usually more than 70%) at an ambient temperature of 45 °C in hot season. The main causes of maintenance include the thermal efficiency decrement and pressure drop increment because of fouling, leakage or intermixing of two fluids due to gasket failure. Under normal conditions, each of these heat exchangers has a routine inspection and maintenance schedule after four months in service to prevent the unexpected shut down of plant. The routine maintenance procedure includes low pressure (less than 20 barg) water jet cleaning, visual inspection of plates and gaskets, failed gasket and plate replacement and assembly of heat exchanger. Furthermore, the cleaning in place (CIP) with chemical reagents and Back flashing method are using to cleaning of heat exchanger without disassemble.

The aim of the present work was to identify and quantify the mode and principal causes of corrosion failure in the PHE by using appropriate analysis methods including visual inspection, optical and scanning electron microscopy, energy dispersive X-ray spectroscopy (EDS), thermo-scan analysis, and measurement of chloride and sulfide content of the waters.

2. Materials and methods

The plate heat exchanger (PHE) of JPC has 56 special stainless steel plates (ASTM A240 Type.316) with special sealing gaskets between them. The practical thickness of the plates is 0.5 mm without any coating. A schematic view of PHE is presented in Fig. 1. This heat exchanger is using for cooling of the hot transport water (TW) by cooling water (CW). Both transport water (TW) and cooling water (CW) are de-mineralized with a maximum content of 50 ppm Cl⁻ and 8–10 ppm dissolved oxygen. The operating condition of failed PHE of JPC is shown in Table 1.

The majority of the cracks have appeared in the upper gasket seat and also some cracks have been observed under two sideward gasket seats of the PHE. In addition, the around of these cracks has been covered with a rusty layer as shown in Fig. 2.

The chemical analysis of plates was done by PMI-MASTER Pro spark emission spectrometer and results are shown in Table 2.

The temperature analysis was applied by SATIR HY-G90 infrared camera. The specimens for optical microscopic analysis prepared according to ASTM E3-11 and micro etch treatment had done as per ASTM E407-11 by Glyceria.

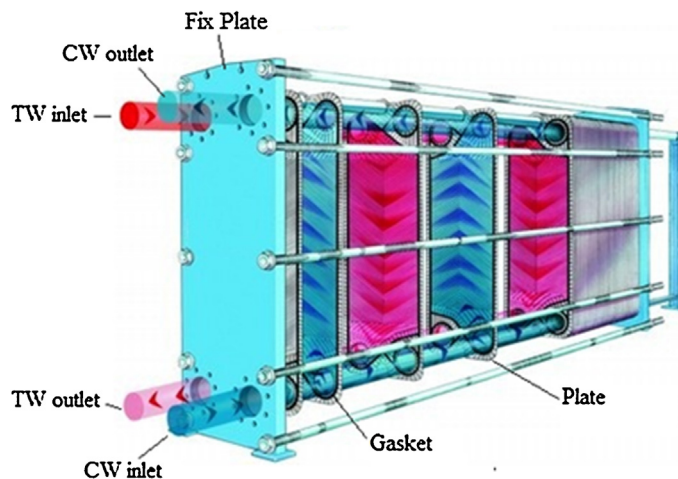


Fig. 1. Schematic of plate heat exchanger.

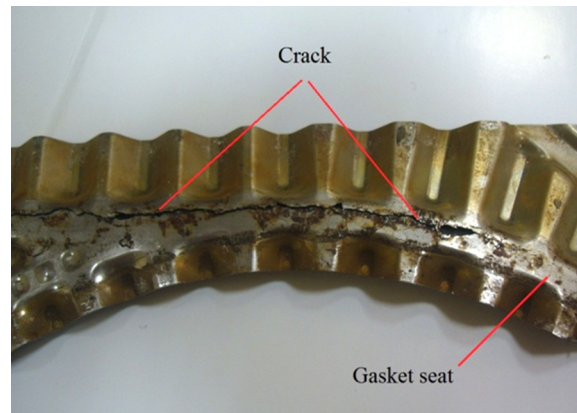


Fig. 2. Appearance of a crack on the gasket seat of heat exchanger plates.

Table 1

Operating condition of failed PHE of JPC.

Water	Inlet temp. (°C)	Outlet temp. (°C)	Inlet pressure (barg)	Outlet pressure (barg)
TW	80	70	4.9	4.4
CW	38	48	6.5	6

Table 2

Chemical composition of plates of heat exchanger.

Element	C	Mn	Si	Cr	Ni	Mo	Ti
Wt%	0.08	1.46	0.12	15.2	11.1	2.11	0.05

3. Results and discussion

3.1. Visual inspection

Generally the visual inspection by naked eye is the first step to roughly estimate the type and cause of failures. As it can be observed in Fig. 3, the branched cracks alongside the gasket seat grooves of plates are present and also, some corrosion pits are visible around these grooves. These pits can act as the start points for the propagating of cracks over the plates when the mechanical stress is present in the system [7]. Although the border areas of plates are not in contact with the cooling or transport water, there are many crevices between them which are subjected to the pitting by crevice corrosion. Fig. 4 shows such pits on the border areas of the plates.

In addition of the pitting corrosion, the presence of a brownish layer on the gasket seat grooves is an indicative for the corrosion occurrence. However, there is no significant sign of pitting in the interior/central parts of the plates despite the fact that these parts contribute in the cooling process and the water flows across them.



Fig. 3. Presence of cracks and pits on gasket sitting groove.

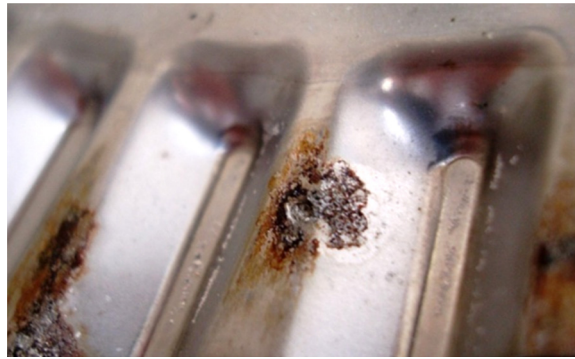


Fig. 4. Pitting corrosion on border area of failed heat exchanger plates.

3.2. Microscopic analysis

Three samples namely 1, 2 and 3 were prepared from three different plates for microscopic studies.

3.2.1. Sample 1

Regarding the microstructure of Sample 1 presented in Fig. 5(a) and (b), the structure includes the austenitic matrix with some intergranular and transgranular cracks. According to SEM image shown in Fig. 5(c), these cracks are relatively sharp and straight passing through the boundaries and austenitic grains. The branched cracks are typical signs of SCC [6–8].

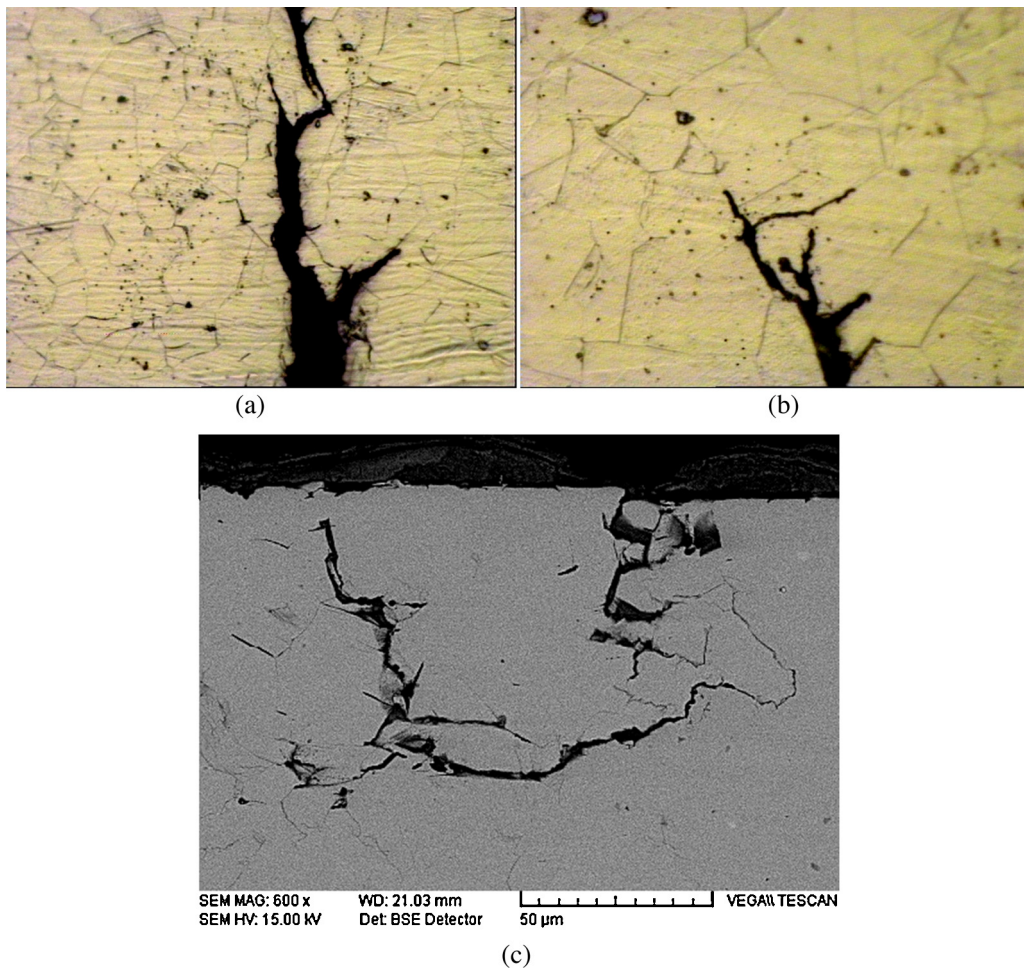


Fig. 5. (a) and (b): Microstructure and (c) SEM of Sample 1.

Intergranular SCC also commonly indicates the contribution of corrosion process in the cracking of plates [9] and on the other hand, the appearance of transgranular SCC in the microstructure of the plates confirms the high mechanical stress conditions [10]. Garcia et al. reported that transgranular SCC susceptibility decreases at lower level of cold stress but the intergranular SCC susceptibility increases [10]. The superimposing of residual stresses leads to the cold forming of the plates and on the other hand, the stresses resulted from temperature/pressure fluctuations as well as the repair and maintenance stresses are the main sources of SCC. The small black dots observed in Fig. 5(a) and (b) are assigned to the micro-pits distributed in the microstructure.

3.2.2. Sample 2

Based on the microstructure of Sample 2 shown in Fig. 6(a), the structure includes the austenitic matrix with some intergranular and transgranular cracks similar to Sample 1. Fig. 6(b) implies the presence of some twinning in the microstructure of sample. As a matter of knowledge, the twinning phenomenon requires high level of stress which can be accounted as a sign for high residual and/or applied stress in the microstructure of plates due to the plastic deformation [11]. The SEM image of Sample 2 (Fig. 6(c)) shows the growth of cracks in several directions in the tip of a primary crack. These micro-cracks are additional supportive evidences for SCC.

3.2.3. Sample 3

As can be seen in Fig. 7(a) and (b), the microstructural features of Sample 3 is similar to Samples 1 and 2. There is a micro-pit as a start point for SCC (Fig. 7(b)). Also, the tip of crack contains some corrosion products according to the SEM image (Fig. 7(c)). This indicates that the corrosion plays an important role in the failure of plates and the formations of cracks stems from the simultaneous occurrence of corrosion and mechanical stress.

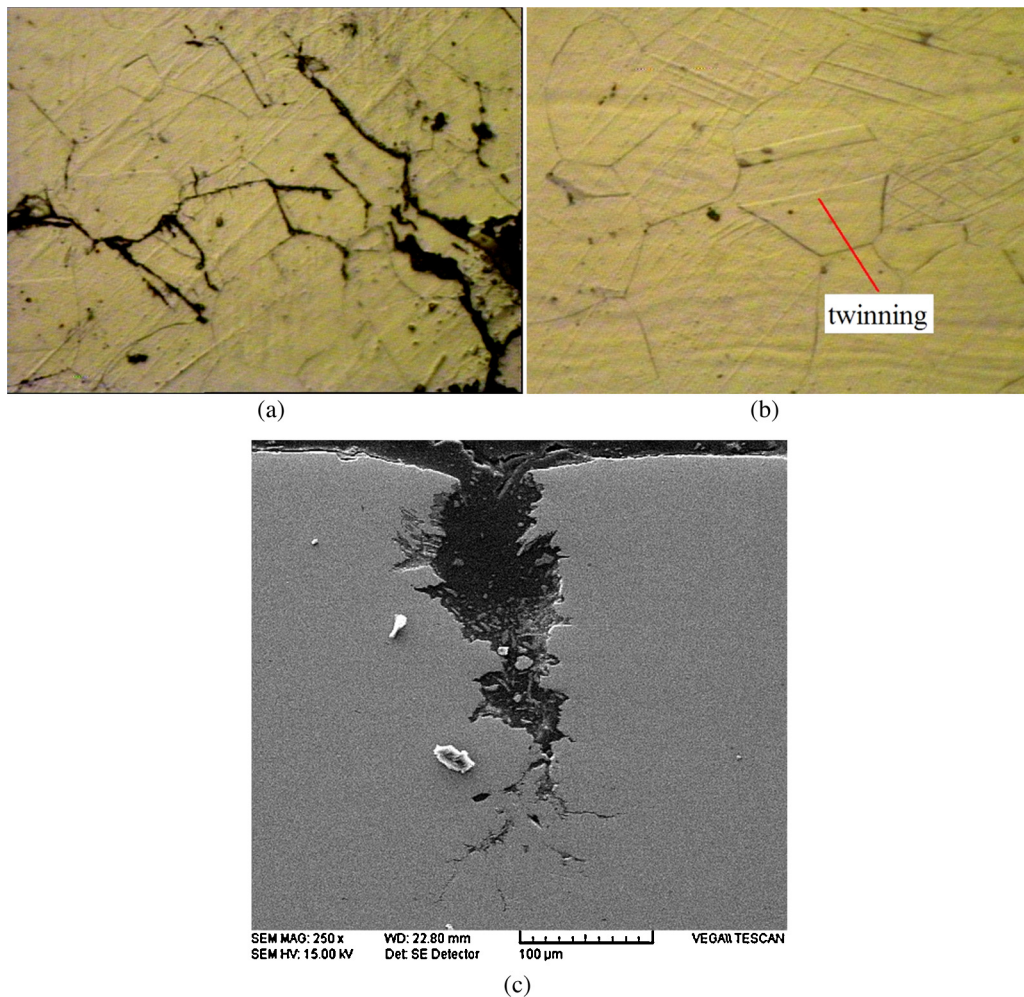


Fig. 6. (a) and (b): Microstructure and (c) SEM of Sample 2.

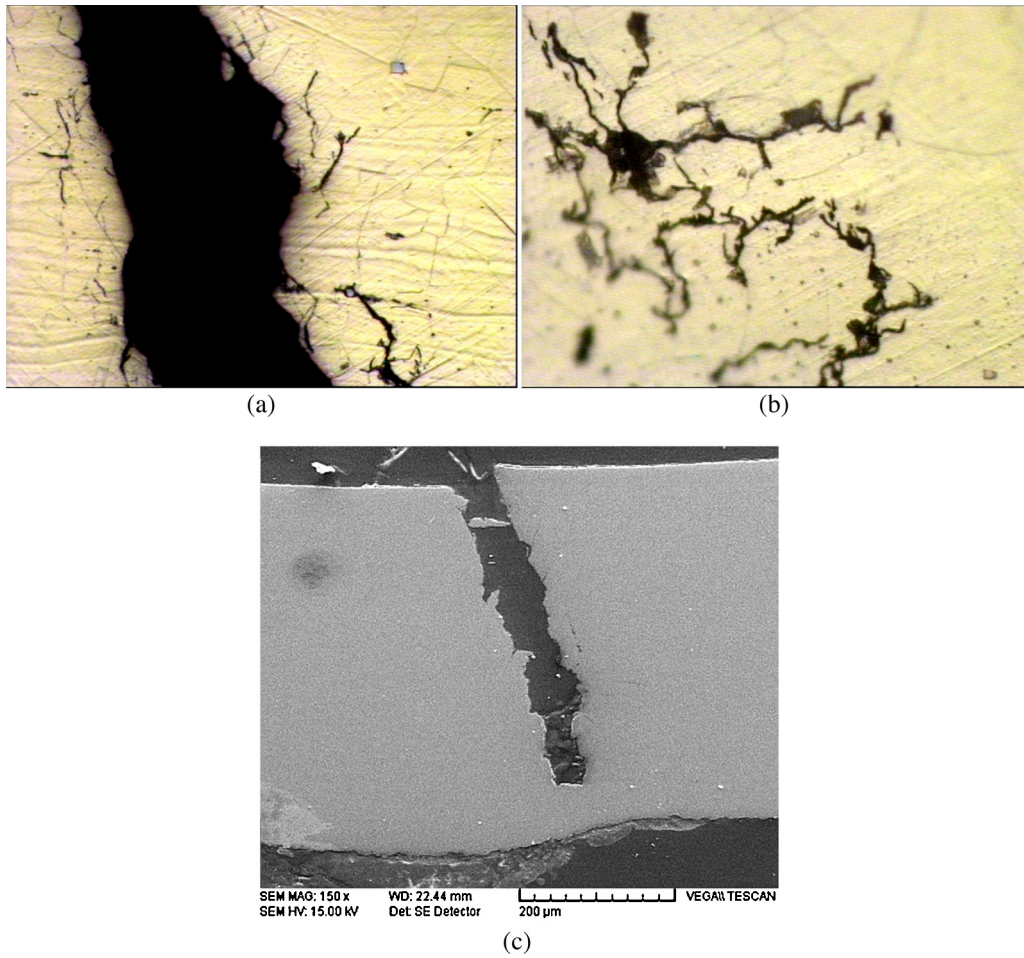


Fig. 7. (a) and (b): Microstructure and (c) SEM of Sample 3.

3.3. EDS analysis

Energy dispersive X-ray spectroscopy (EDS) of the brownish (rusty) layer formed around and in the cracks is shown in Fig. 8. According to EDS spectrum, the brownish (rusty) layer contains Fe, Cr, O as well as S and Cl. Fig. 8 shows the EDS

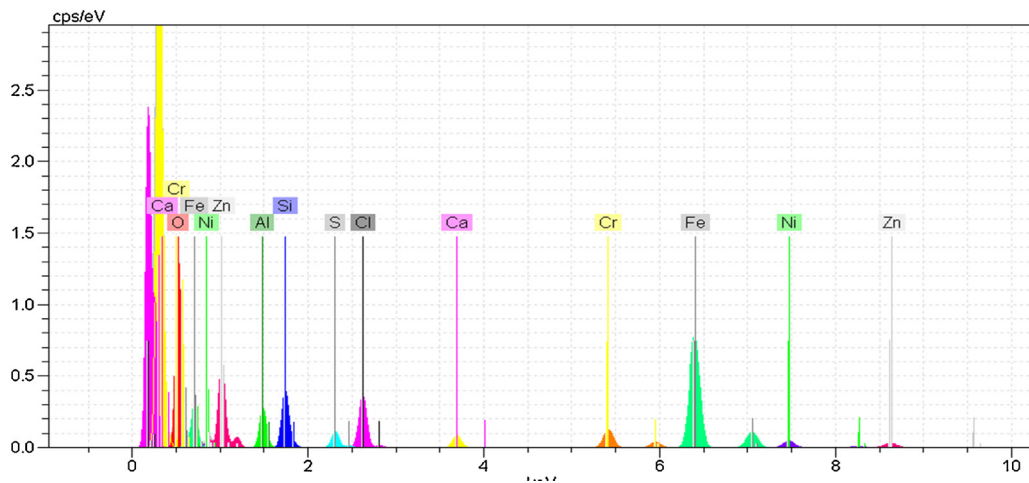


Fig. 8. EDS analysis of corrosion products in Sample 1.

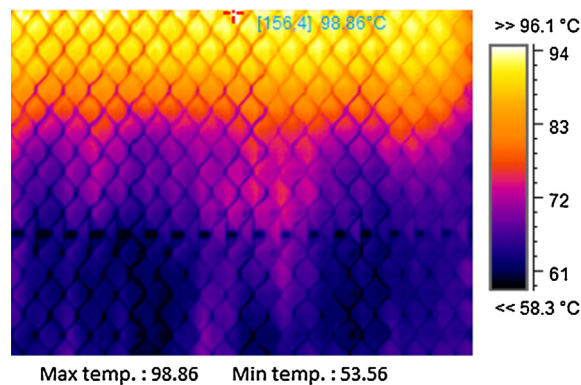


Fig. 9. Temperature profile of TW inlet.

analysis of Sample 1. The presence of Fe, Cr and O can be attributed to the corrosion products of S.S 316 [11]. The presence of chloride in the EDS spectrum also confirms the contribution of Cl^- in pitting corrosion of the protective layer of 316 stainless steel plates. It can be concluded that the formation of the pits and the presence of stress can lead to Cl-SCC failure of plates. Also, sulfide ion can significantly accelerate the SCC failure of the plate [6].

3.4. Thermo-scan analysis

Temperature analysis was conducted via infrared camera for the evaluation of the temperature profile of several areas of PHE. According to thermo-scan result illustrated in Fig. 9, the maximum temperature of the exchanger is around 99 °C in the top of PHE that belongs to TW inlet of exchanger. The value of temperature is higher than the design temperature of heat exchanger. The history of equipment revealed that in a period of operation around one year ago, the temperature of TW increases due to some process changes. During this period, the water that called service water (SW) was poured over the PHE to increase the cooling rate and reduce the TW outlet temperature. Moreover, as it can be seen in Fig. 3, there is a brownish layer over the zigzag edge of plates which imply the presence of suspended soil in the service water.

3.5. Chloride and sulfur concentration measurement

The chloride and sulfide content of the TW, CW and SW were measured for the confirmation of SCC postulation. However, the results show the both chloride and sulfide contents are around 1–3 ppm in all waters. According to API 571-4.5.1.3, there is no definite minimal limit for chloride ions because the local concentration of chloride ions can always occur. Therefore, although the chloride and sulfide ions levels of SW is low, the evaporation of SW in crevices due to high temperature of TW inlet and CW outlet, can lead to locally concentration of these ions. Similar observations have been reported about the local chloride-buildup at high temperature in crevices [4,8].

4. Conclusions

In this study, the principal causes of corrosion failure in the plate heat exchanger (PHE) of Jam Petrochemical Complex (JPC), Asalouyeh, Iran, were evaluated via visual inspection, optical and scanning electron microscopy, energy dispersive X-ray spectroscopy (EDS), thermo-scan analysis, and measurement of chloride and sulfide content of the waters. It was found that the chloride ions build-up in crevices formed between plates and gaskets (at high temperatures), is the main reason for the occurrence of SCC. The suspended soil of the service water settled in the crevices between gasket and plate and provides a favorable position (dead zone) for building-up of the chloride ions. When the level of chloride ions in the water is low, the evaporation of water in the crevices leads to chloride ions build-up. Moreover, the high temperature of the transport water outlet and cooling water inlet results in the acceleration of this building-up. By chloride ions concentration in the crevices, the pitting corrosion under gasket seat occurs. In addition, the simultaneous presence of chloride and sulfide ions intensifies the SCC failure in the heat exchanger plates.

5. Recommendations

Since the appearance of the cracks in the heat exchangers occurs after cooling the TW outlet by the service water (SW), the use of higher number of the plates in the heat exchangers together with the higher flow rate of cooling water is strongly recommended; in this way, at a constant flow rate of transport water, not only the temperature of transport water is decreased but also the SCC cracks resulted from the direct contact of the service water (which usually contains some levels of Cl^-) can be effectively avoided.

Acknowledgments

The author would like to acknowledge the Jam petrochemical complex inspection department for their cooperation.

References

- [1] Dean KM, Virk MA, Haque CI, Ahmad R, Khan IH. Failure investigation of heat exchanger plates due to pitting corrosion. *Eng Fail Anal* 2010;17:886–93.
- [2] Elsariti SM. Haftirman Behaviour of stress corrosion cracking of austenitic stainless steels in sodium chloride solutions. *Proc Eng* 2013;53:650–4.
- [3] Della rovere CA, Castro-Rebello M, Kuri SE. Corrosion behavior analysis of an austenitic stainless steel exposed to fire. *Eng Fail Anal* 2013;31:40–7.
- [4] Guang XJ, Yu Peng X, Ai Hua T. Corrosion failure analysis of the condensate collector vessel head of evaporation system in ethylene glycol device. *Eng Fail Anal* 2012;22:113–20.
- [5] Orlikowshi J, Krakowiak S. Pitting corrosion and stress-corrosion cracking of buffer tanks in a brewery. *Eng Fail Anal* 2013;29:75–82.
- [6] Yongde L, Na X, Xiaofeng W, Junbo S, Lili Z, Mei Z, Qishan Z. Failure analysis of the 304 stainless steel tube in a gas analyzer. *Eng Fail Anal* 2012;20:35–42.
- [7] Ziaei SMR, Mostowfi J, Golestani Pour M, Ziaei SAR. Failure analysis: chloride stress corrosion cracking of AISI 316 stainless steel downhole pressure memory gauge cover. *Eng Fail Anal* 2013;33:465–72.
- [8] Ahmad TM, Alfantazi A, Budac J, Freeman G. Failure analysis of 316L stainless steel tubing of the high-pressure still condenser. *Eng Fail Anal* 2009;16:1432–41.
- [9] Huang YZ, Titchmarsh JM. TEM investigation of intergranular stress corrosion cracking for 316 stainless steel in PWR environment. *Acta Mater* 2006;54:635–41.
- [10] Garcia C, Martin F, De Tiedra P, Heredero JA, Aparicio ML. Effects of prior cold work and sensitization heat treatment on chloride stress corrosion cracking in type 304 stainless steels. *Corros Sci* 2009;43:1519–39.
- [11] Psyllaki PP, Pantazopoulos G, Pistoli A. Degradation of stainless steel grids in chemically aggressive environment. *Eng Fail Anal* 2013;35:418–26.