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An overview of the localized corrosion problems in seawater desalination plants — Some recent case studies

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ABSTRACT

Uniform corrosion, localized corrosion (pitting and crevice corrosion), cavitation, stress corrosion cracking, corrosion and mechanical fatigue, galvanic corrosion, dealloying, etc., are the common types of corrosion by which materials in desalination plants are subject to deterioration. Carbon steel, austenitic stainless steels, cupronickel alloys and titanium are prevalent materials in a modern day desalination plant. However, the majority of the failures in multistage flash (MSF) and seawater reverse osmosis (SWRO) plants have been attributed to localized attack. Localized attack in the form of pitting and/or crevice corrosion arise due to stagnation of chloride containing water, CO_2 attack, presence of internal stresses, weld defect, foreign material carryover, mismatch of the material, etc. Flash chamber, pipelines, pumps, valves, heat exchanger, demister, storage tanks, intake system and power generating ancillary units may be affected by local attack. Right selection of material, skillful control of environmental conditions and thoughtful design can create the situation ideal for proper operation of the plant. In recent years, introduction of new materials such as high alloy stainless steels, metal matrix ceramic/plastic composite and polymer coatings has resulted in lowering down the cases of failure due to local attack and thus increasing the efficiency of plant. This paper presents an overview of the localized corrosion problems arising in different components of desalination plants with particular emphasis on the need of applying new materials which would likely restrict the damage due to corrosion. Also, some recent case studies during the last decade are cited covering the highlights of the problem, causes, mechanism and recommendations. The selected case studies include corrosion of flash chamber bottom plates, failure of micron cartridge filter in a SWRO plant, duplex steel bolt failures in a desal pump, failure of bottom plate of a potable water tank, failure of a cement-mortar internally lined water transmission pipeline, premature failure of repainted epoxy coating on the internal bottom plate of a fuel oil tank, failure of a high pressure pump motor bearing oil cooler, leakages in the weldments of a brine rejection pipe in a SWRO plant, failure of a water transmission line and shearing of a shaft in a brine recycle pump.

Keywords: Localized corrosion; Seawater; Desalination plant

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1. Introduction

One of the striking features of seawater desalination plants is the application of a variety of metallic and non-metallic materials of diverse properties. Carbon steel, stainless steels, cupronickel alloys, titanium and fiber reinforced plastics (FRP) are the prevalent materials in a modern day desalination plant. Thermal desalination operates under varying environments ranging from highly corrosive seawater to distilled water containing significant to trace amounts of dissolved gases or carry over metallic or non-metallic substances, and non condensing vapors. Uniform corrosion, localized corrosion (pitting and localized corrosion), cavitation, stress corrosion cracking (SCC), corrosion and mechanical fatigue, galvanic corrosion, dealloying, intergranular corrosion, hydrogen embrittlement, etc., are the common types of corrosion by which materials are subject to deterioration [1–3]. The majority of the failures in multistage flash (MSF) and seawater osmosis (SWRO) plants have been attributed to localized attack. Localized attack is usually in the form of pitting and/or crevice corrosion. Whilst pitting arises due to stagnation of chloride containing water, CO_2 attack, presence of internal stresses, weld defect, foreign material carry over, mismatch of material, the crevice corrosion is observed in crevices occurring in overlapping surfaces, under seal and gaskets, elbows and similar areas [2,4,5].

Pitting is most insidious form of corrosion which causes failure by penetration with only a small percent weight loss of the entire structure. It is most destructive in the sense that usually the repairs are not possible and entire structure has to be replaced. The most important condition for the pitting to occur is that the metallic surface must be in a passive state. The process of pitting destroys the protective film at certain sites, resulting in the loss of passivity and initiation of pits on the metal surface. Factors affecting the pitting include surface defects (inclusion such as sulfide and second phase such as intermetallic), degree of cold work, surface finish, sensitizing temperature, velocity and environmental conditions [3,4,6]. The pits also provide active crevices for a formidable corrosion attack. In most cases, pitting is a precursor of crevice corrosion and there are obvious similarities of crevice and pitting corrosion mechanisms. The pitting behavior of austenitic steels which have been prime construction materials for desalination plants has been the subject of numerous studies [5–12]. Pitting appears to be the most affective factor responsible for corrosion failure in plants [4].

Crevice corrosion is caused by the accumulation of deposits on a metallic surface or by the existence of gaps and cavities between adjoining surfaces [6,10,12,13]. An important condition is the formation of a differential aeration cell for crevice corrosion to occur. Certain steels like type 304 (UNS S30400)/type 316 (UNS S31600) can be subjected to crevice corrosion in chloride environments such as brackish water and seawater. Crevice corrosion is affected by alloy composition, passive film character, geometry bulk composition media, transfer in and out of crevices, temperature and oxygen [10,14–16]. Generally, the larger is the bold area (cathodic) and smaller the creviced area (anode), the lesser the possibility of crevice corrosion. It is generally agreed that the mechanism of crevice corrosion [14,17,18] involves 4 distinct stages: (i) deoxygenation of the crevice solution, (ii) the period of steady development of aggressive solution within the crevice, increase of Cl^- concentration and fall of pH, (iii) break down of passivity when the aggressive solution within the crevice reach the critical service solution pH and (iv) onset of propagation stage.

High chromium containing Ni-base alloys (Ni-Cr-Mo) were used as a possible replacement for stainless steels to combat localized corrosion. However, the prohibitive cost of Ni-base alloys has severely restricted their application. Based on the fact that Cr and Mo have a synergic effect in enhancing the pitting resistance of steel in seawater, 6% Mo containing stainless steels so-called high alloy stainless steels were introduced in the 1970's and 1980's and their use has been continued up to this time. The application of conventional and high stainless steels in marine environments has been dealt with in a number of review and articles [19,20].

The corrosion behavior of some conventional and high alloy austenitic, ferritic and duplex SS has been studied at 50°C in the Gulf seawater [21]. The results of the studies indicate that the presence of alloying elements such as Cr, Mo and Ni has significant and beneficial influence on the pitting and corrosion resistance by shifting the critical potential in the noble direction.

The key factor in selecting material for a high pressure system SWRO plant is to choose a SS grade which can resist crevice corrosion as the RO system may incorporate many crevice sites at the pitting connection which are usually O-ring types, gasket or metallic composition fittings. For SWRO, 6% Mo high SS 254 SMO (UNS S31254) or precipitation hardenable 1925 hMO (UNS NO8926) have been successfully employed [22]. Electrochemical studies showed that austenitic type 316 (UNS S31600) and type 317 (UNS S31700) were the least favored for the construction of SWRO plants. Austenitic Cr-Ni-Mo stainless steels: UNS S31726, UNS S31254 and UNS S32250, ferritic UNS S44635, duplex UNS N06250, solid solution strengthened Incoloy 825 (UNS N08825), Ni-Cr-Mo alloy UNS N08904 and UNS N10276 are good alternatives for the construction of RO units, however, the initial cost is high [23]. A study was carried out on the corrosion behavior of high alloy stainless steels include 254 SMO (UNS S31254) and Al-6XN (UNS N08367) and duplex 2205 (UNS S31803), SF 2507 (UNS S32750) and DP3W (UNS S32974). The results of the study show that all the alloys appear to have excellent resistance to pitting but alloy 2205 (UNS S31803) is vulnerable to a crevice forming environment. In seawater, DP3W (UNS S32974) possessed the best resistance in a crevice-forming environment.

The literature is abound with investigative studies relating to failure of materials in seawater handling and processing systems including desalination plants. A study was concerned with the thinning and ultimate perforation of a type 316L heat exchanger tube of 15 mm diameter [24]. The tube had an original wall thickness of 0.8 mm and failed after a relatively short time in service. The investigation showed that the heat exchanger had thinned to perforation due to general corrosion from inside of the tube as there was no corrosion on the outer side of the surface. The cause of the failure was plastic deformation which occurred due to increased pressure that was encountered as a result of vaporization of the superheater water stream that escaped from the perforation in the tube.

Cupronickel (UNS C70600 and UNS C71500) condenser tubes carrying seawater were found to undergo failure [25], which was proceeded by extensive overall thinning, formation of shallow channels, pits and grayish black internal deposits in one of the units. In another unit, tube failure was noticed without any significant overall thinning and the presence of adhered hard and black deposits. The increased velocity of seawater as well as the deficiency of iron in the cupronickel alloy had resulted failure in one case whereas relatively low velocity of water associated with the deposition of sludge and biofouling was the cause of failure in the other. The failure of the tubes could be prevented by maintaining the right velocity of seawater.

A seawater pump shaft failed due to pitting [26]. The shaft was operated for 17 years. The localized attack resulted in the formation of holes and cavities in the metal. The relatively stagnant liquid conditions, which exist between the shaft and sleeve during the pump operation as well as periods of shut down create ideal conditions for pit initiation. The bronze shaft sleeve on removal revealed severe pitting in the area directly under the sleeve. The severity of attack in this case suggests that pitting might have been assisted by galvanic effect between the steel shaft and the bronze sleeve.

Failure in grey cast iron pipes of domestic water transmission pipelines was investigated [27]. There were 5 different pipes showing four different failure modes. Two failed by circumferential cracking, one by bell split, one by a blow out of part of the pipe wall and the fifth by manufacturing flaws. Bell split occurred because of a small corrosion pit causing localized weakness. The pipe blow down occurred when corrosion/graphitization had reduced the strength of the pipe wall in local area to a point when a pressure surge caused the wall to rupture. In circumferential break, the pipe failure occurred by a crack initiated at the corrosion pit. The crack then propagated most of the way around the pipe and failure took place, severing the pipe. The fifth pipe failed due to manufacturing flaw which was either due to poor metallurgical control or presence of network of pores or pits as large as 2 mm across or presence of inclusions such as ferrosilicon.

Case studies relating to the investigations on failures in SWCC desalination and power plants are well documented in literature. These include: failure of micron cartridge filter components in a SWRO plant [28], premature failure of repainted epoxy on the internal bottom plate of a fuel oil tank [29], investigation of the failure of a high pressure pump motor bearing oil cooler [30], premature water-side corrosion of furnace wall tubes in a high pressure boiler [31] and corrosion of flash chamber plates in a MSF desalination plant [32].

Some case studies relevant to failure in SWCC plants by localized corrosion modes are accounted as follows.

2. Case I. Corrosion of flash chamber floor plates in a multistage flash (MSF) desalination plant

The evaporator has 16 stages (cells) in which first 13 are heat recovery and the last 3 are heat rejection stages. The flash chamber plates were made of carbon steel with AISI 317 SS internal cladding. Approximately 4 years after the plant was commissioned, indication of corrosion processes in the form of numerous red-colored spots was noticed on the floor plates of stages 11–16. Upon cleaning the red spots, pits were found in the middle of the spots with slightly wet outer surfaces (Fig. 1).

The results of investigations based on NDT, metallography, SEM and EDX techniques indicate damage to the floor plates due to localized corrosion. The incomplete drainage of high chloride water from stages 11–16 floor plates during shut down (Fig. 2) resulted in a fairly long period of stagnancy which produced conditions favorable to pitting corrosion of austenitic stainless steel. The SEM picture of the corrosion products inside the pit show cluster of porous materials mainly comprised of NaCl in very high concentration and SiO_2 and Al_2O_3 in very small amounts as revealed by EDX studies (Fig. 3). The absence

Fig. 1. Corrosion spots after grinding to 1 mm depth.

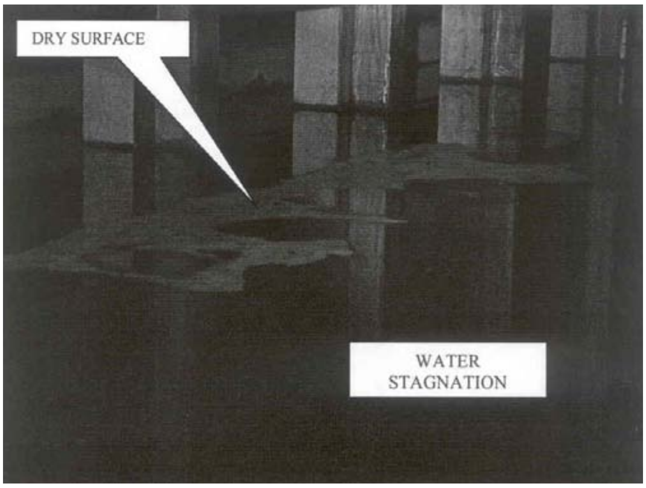

Fig. 2. Desalination Line 13, water stagnation in Cell 14, bottom floor.

of drainage has been attributed to uneven level of floor plates of different stages of the desal unit.

It was recommended that the design of the flash chamber cells should be reviewed with special reference to the floor levels 1–10 and 11–16. Also, the provision of additional drain between chambers 11–15 should be made.

3. Case II. Failure of micron cartridge filter (MCF) in a seawater reverse osmosis (SWRO) plant

Corrosion of a MCF used in a 20 MIG SWRO plant was reported. The MCF had been in use for the last 6 months and the components were in constant contact with treated seawater. The components were made of 904L SS [UNS N08904].

The local attack brought about the crevice corrosion appearing to be the cause of failure of the cartridge filter. This is substantiated by the following observations:

(i) Pits on the surface of the bottom cap (Fig. 4).
(ii) The presence of thick deposits of corrosion products at the threadings of the bottom cap (Fig. 5) which are rich in chloride as evidenced by the EDX spectrum (Fig.6), which shows strong peak of the chloride.
(iii) The SEM image of corroded cartridge filter shows the presence of aggregates of dark brown powdery like products (Fig. 6).
(iv) The corrosion marks on the stud, bottom face of the flange, O-ring slots, threadings of embedded nuts and hexagonal nuts.

It was recommended to use either a superaustenitic stainless steel or a suitable polymeric material for preventing the possibility of localized attack in MCF.

4. Case III. Investigation on the bolt failure in a desal pump

The bolts were found cracked during the disassembly of the unit of a desal pump (Figs. 7 and 8). The bolts were used to hold the bearing spider with lower and upper column pipe. The pump was partially submerged in seawater and the bolts remained submerged completely. The bolts were made of duplex 1.4460 and had been in use for more than 10 years. The nuts of the bolts were made of duplex 1.4462 and indicated no corrosion.

The bolts might have corroded at the crevices by local attack for long periods of time under seawater immersion conditions. This along with stresses also initiated corrosion fatigue (Fig. 9). The duplex steel material was corroded by local attack under the influence of several factors, namely, the availability of many crevice sites in the bolt, coarsened structure of the alloy matrix (Fig. 10) and long exposure to seawater. For bolts subjected to long exposure of seawater in presence of crevices and under

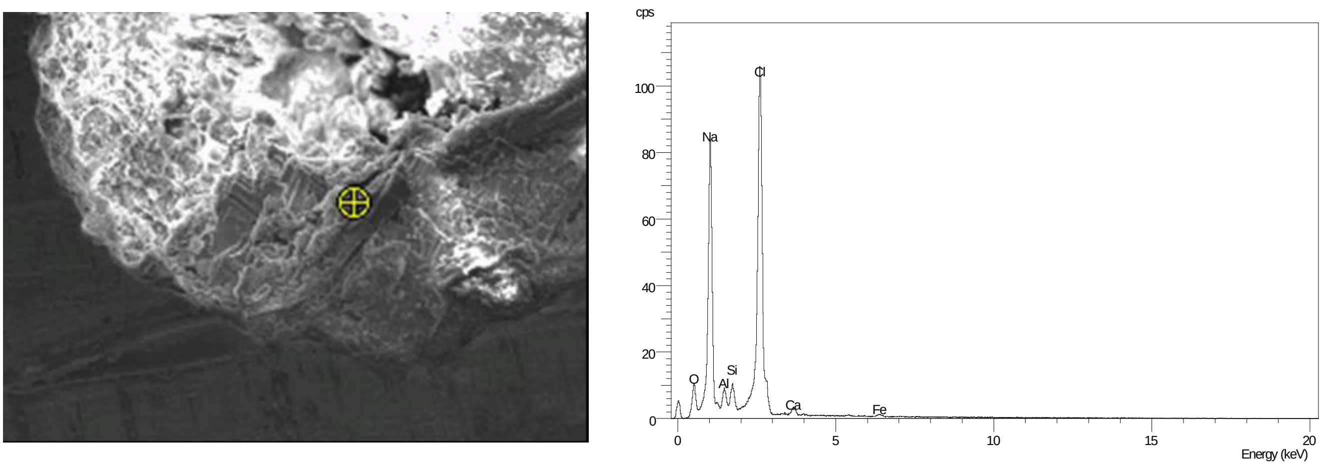

Fig. 3. SEM picture and EDX profile of the corrosion products (inside the pit).

Fig. 4. Bottom of micron cartridge filter cap showing reddish brown corrosion products at the center.

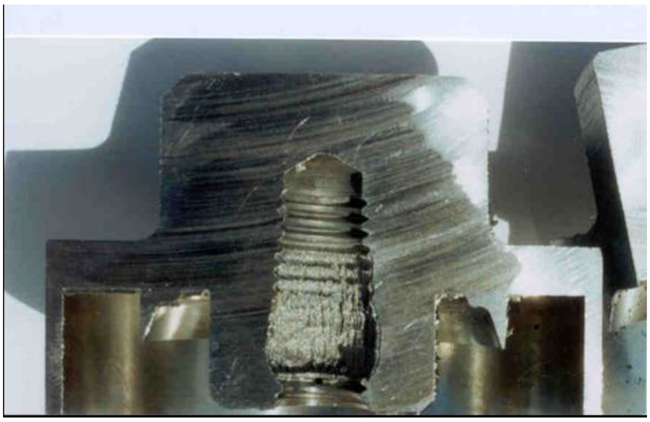

Fig. 5. Corrosion product deposits on the threading (female) due to crevice corrosion.

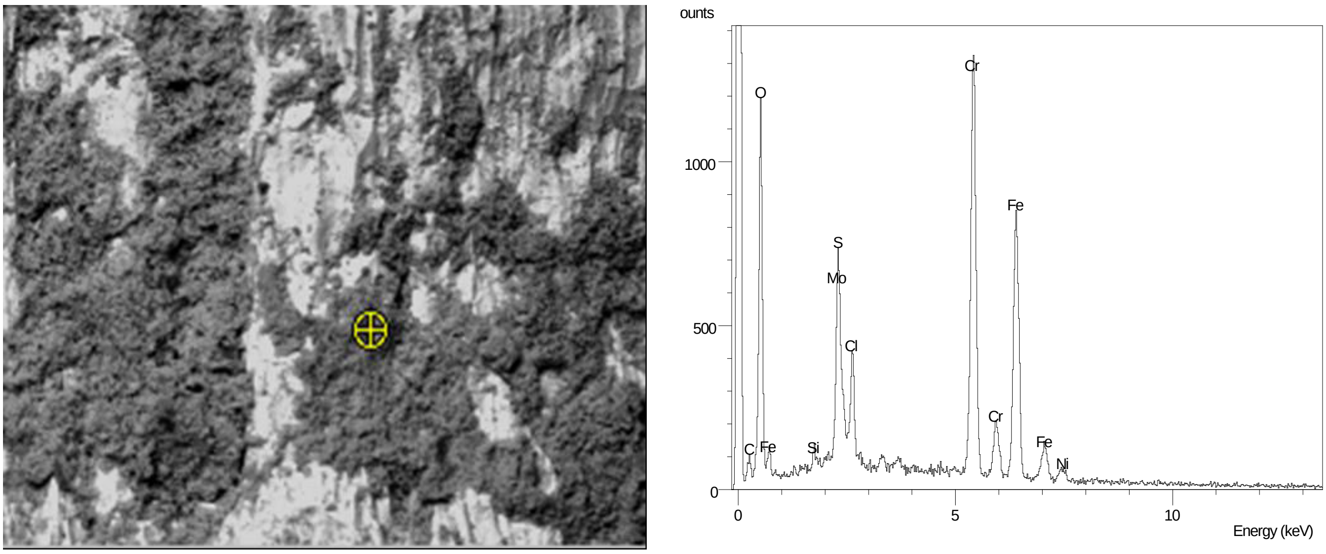

Fig. 6. EDX profile of the corrosion products on stud thread of the micron cartridge filter.

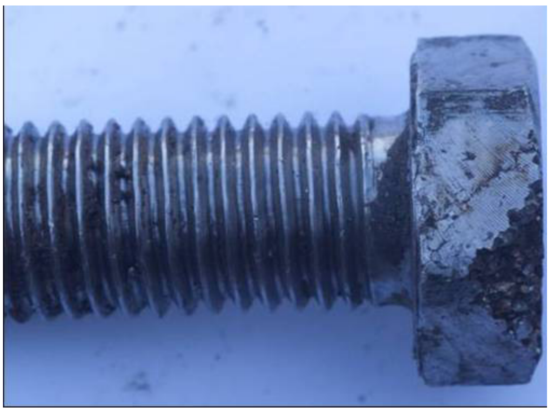

Fig. 7. Photograph showing the surface of the head of the failed bolt.

Fig. 8. Photograph showing fracture mode of the bolt at the metal surface near the bolt head showing regions of depression and protrusion.

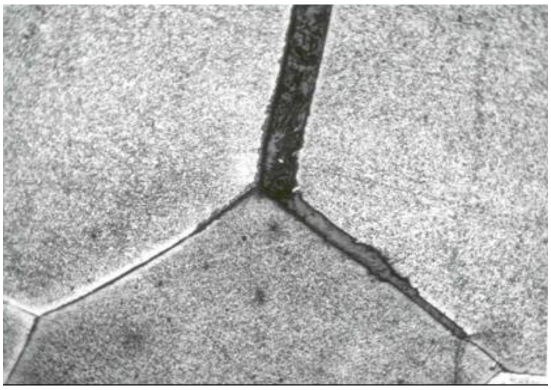

Fig. 9. Photomicrograph of the cross-section of the failed bolt showing initiation of an intergranular crack 100 ×.

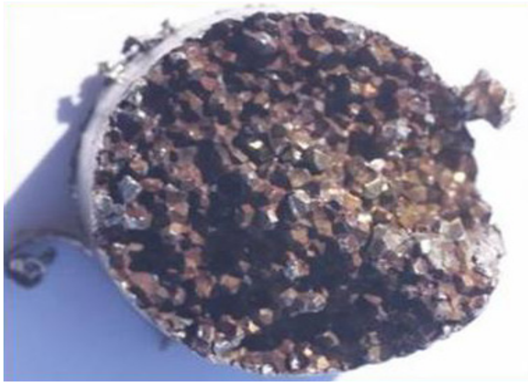

Fig. 10. Photograph showing fracture surface having coarse granular texture with brownish red crystalloids.

dynamic stress conditions, it was recommended to use superduplex with higher Mo content (>3%) along with nitrogen additions.

5. Case IV. Failure of bottom plate of potable water tank in a desalination plant

The presence of holes and deep pitting in the bottom plate of a potable water storage tank was reported (Fig. 11). The tank bottom plate had been in contact with 2 different corroding environments, i.e., potable water in the inner side and soil on the outer side. The inner surface was protected against corrosion by a combination of epoxy coating and CP whereas the outer surface was protected by a layer of asphalt and C.P. A study of the samples of failed bottom plate and magnetic flux leakage (MFL) report show severe underside and water side corrosion with possibility of simultaneous initiation of the localized process at both the sides.

The water wide corrosion was initiated as a result of blistering in the epoxy coating which led to the localized attack and resulted in pitting and holes (Figs. 12 and 13). The blistering in the coating might be due to malfunctioning of C.P. system. The heavy underside (soil side) corrosion was initiated possibly due to stray DC from impressed C.P. system operating on other tanks in the vicinity. The contact of leaked potable water from inside the tank through holes with underside plates further contributed in accelerating the underside corrosion.

It was recommended to install an integrated CP for all the tanks which could eliminate the possible effect of stray DC.

6. Case V. Failure of a cement-mortar internally lined water transmission pipeline

Water leakage was reported in a 95 km long 500 mm diameter and 6.35 mm thick steel pipeline. The pipes have 8 mm thick cement mortar internal lining and 2.5 mm thick polyethylene external coating. The pipes had joints of X-Pando (MgO based sealant) (Fig. 14). Serious corrosion was observed inside the surface of steel pipes (Fig. 15). No corrosion was observed at the outer surface. The analysis of corrosion products and cement mortar

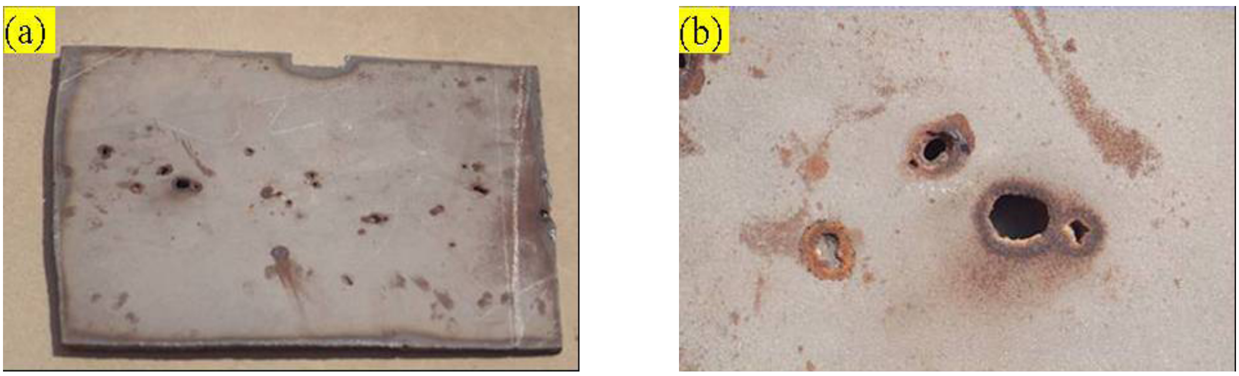

Fig. 11. (a) Inner surface of the bottom plate, cut from a location near the annular plate, in the as received condition (b) A close-up view of the hole and pit.

Fig. 12. Inner surface of the bottom plate cut from a location away from annular plate showing only pits

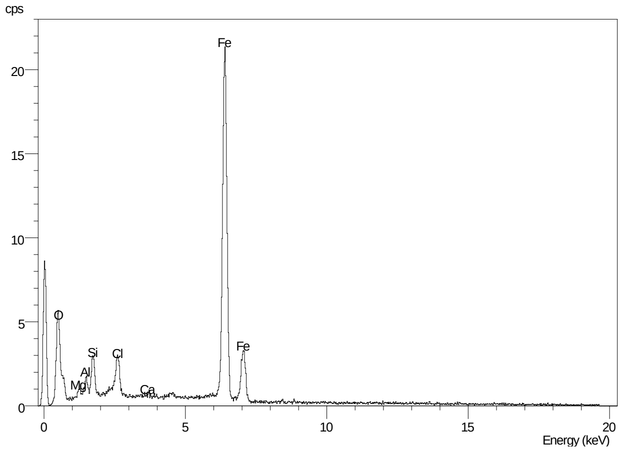

Fig. 13. EDX profile of the corrosion products on the surface of the pit.

Fig. 14. Photograph of internal of pipe sample 4 showing sound pipe.

Fig. 15. Photograph of internal of pipe sample 1 showing disbondment of X-Pando sealant.

samples showed the presence of significant concentration of chloride. The analysis of water in pipe shows a pH of 7.65 with chloride content of 56.7 ppm and sulfate content of 1222 ppm. The source of chloride is most probable from left over water after the hydro-testing and/or flushing.

Visible examination of the pipe, EDX analysis and SEM studies of the pieces from the pipe indicate severe corrosion and the presence of cracks and holes in the internal of pipes (Fig. 16). The EDX of the region around the hole showed presence of Ca and Cl^- besides Fe ((Fig. 17).

The main cause of pipe failure appears to be deterioration or disbondment of X-Pando by the high chloride-sulfate water. This resulted in exposure of the metal to water and in consequence, initiation and subsequent propagation of localized corrosion in the internal of pipe. As the performance of the X-Pando was unsatisfactory at the joints, it was recommended to remove it and replace by a suitable sealant.

7. Case VI. Premature failure of repainted epoxy coating on the internal bottom plate of a fuel oil tank

Corrosion of a repainted epoxy coating over the inner side of the bottom plate of a fuel oil tank, in a desalination and power plant, was reported (Fig. 18). This resulted in the perforation of the bottom plate. According to the report, some cavities and minute pits were already existed on the inner surface of the plate when coating was reapplied but the painters ignored them. After 2 months of service following repairs, penetration of the bottom plate occurred.

The cavities and pits already present on the inner side of the bottom plate of the tank were caused by localized corrosion attack that stemmed from the failure of the original epoxy coating from its long exposure to crude oil (Fig. 19). The failure of repainted coating and subsequent perforation of the plate was again due to localized attack

Fig. 16. Close-up photograph of the external of pipe 1 showing a hole in the metal.

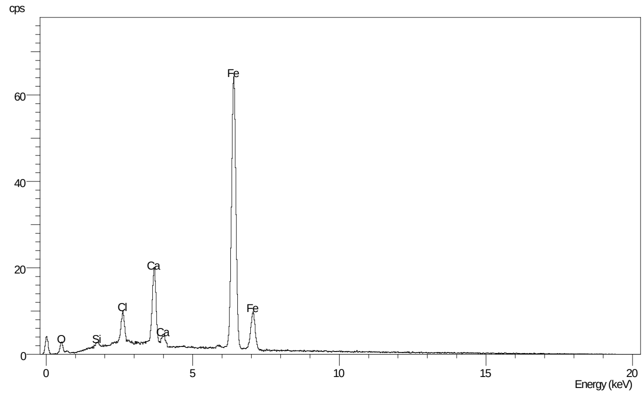

Fig. 17. EDX profile of the damaged area in internal pipe 1.

Fig. 18. Photograph of plate sample in as received condition.

Fig. 19. Photograph showing a large hole in the plate sample.

which was initiated by the chloride and other impurities in the pits and cavities underneath the repainted coating. The presence of chloride and impurities (Si, Mg, Al, K, Ca, Ti and Fe compounds) is indicated by the EDX profile of the corrosion products in the pits (Fig. 20). The SEM image of the corrosion products in the pit indicates the presence of agglomeration of different materials.

It was recommended that in order to avoid failure, chloride decontamination by chemical treatment should be considered as an essential step before repainting. A phosphoric acid based treatment is reported to be effective in such cases.

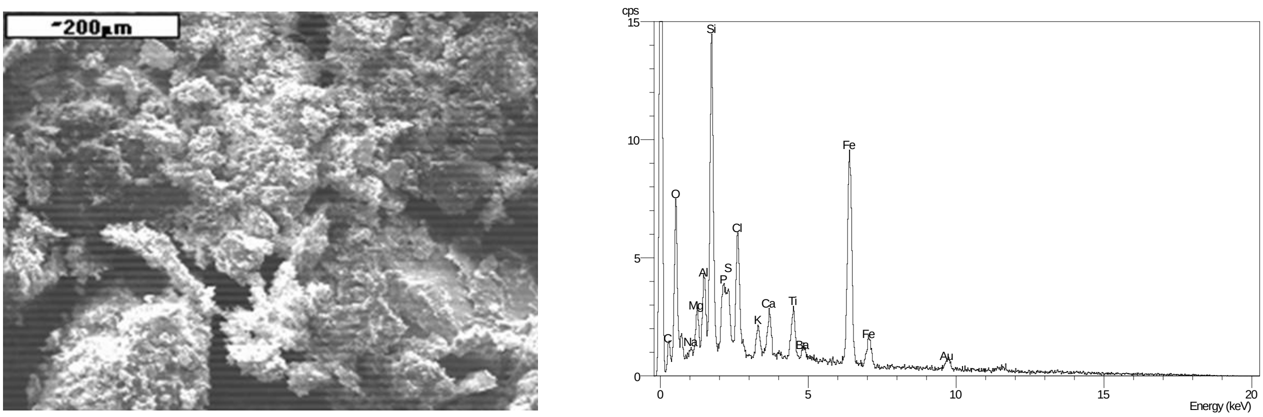

Fig. 20. EDX profile of corrosion products collected from the pits on the plate.

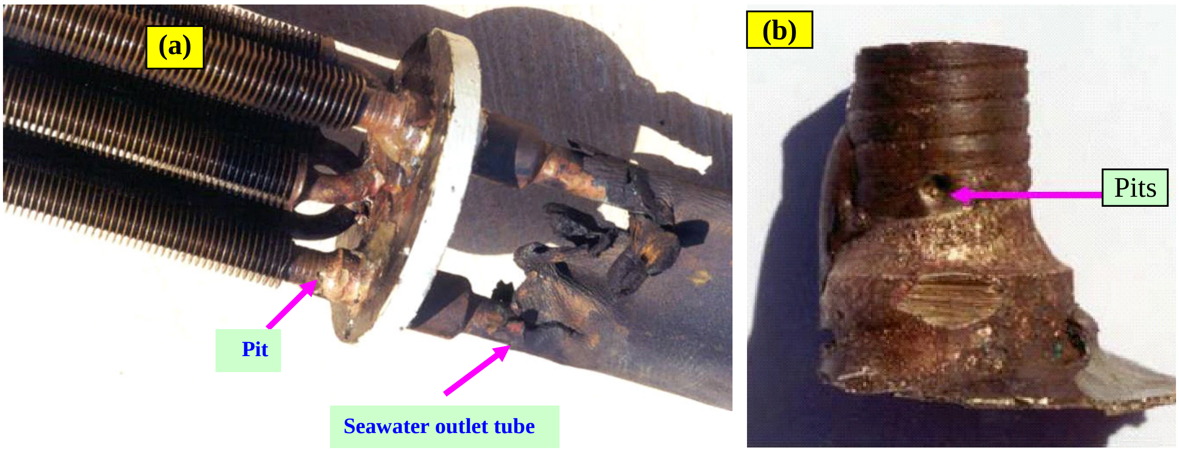

Fig. 21. Photographs of failed oil cooler showing macropits.

8. Case VII. Failure of a high pressure pump motor bearing oil cooler

Failure was reported of a cupronickel cooling coil tube in the main bearing oil cooler of a pump in a SWRO plant (Fig. 21). Failure appeared in the form of pitting at the outlet of the cooling coil tube. The cooling medium was aerated seawater.

Low or near stagnant velocity or the flow of seawater appeared to be the key factor in bringing about the failure. The metallographic and SEM studies indicate that obstructions in the flow path were mainly due to improper welding (Fig. 22).

The results of the investigation led to the conclusion that the cause of the failure could be attributed to localized pitting from the synergic action of a combination of factors, namely, stagnancy, welding heat affected zone (HAZ), the presence of high chloride and sulfates in seawater and induction of subsequent stresses.

It was recommended to carry out tests for soundness of the welding and to adopt measures for keeping the flow path free from foreign obstacles.

9. Case VIII. Leakages in the weldments of brine rejection pipes in a SWRO plant

Leakages were reported at different locations in the weld joints of brine rejection in a 4325 m3/h SWRO plant (Fig. 23).

The pipes, main headers, HP pumps and weld joints were made of AISI 317L SS. Before commissioning, the SWRO plant was under preservation and membranes were preserved using formalin. The pipes showed severe corrosion at the weld joints. The corrosion failure appeared to occur due to long preservation in high salinity water containing formalin which made the water acidic. The stagnancy in water promoted the on set of localized

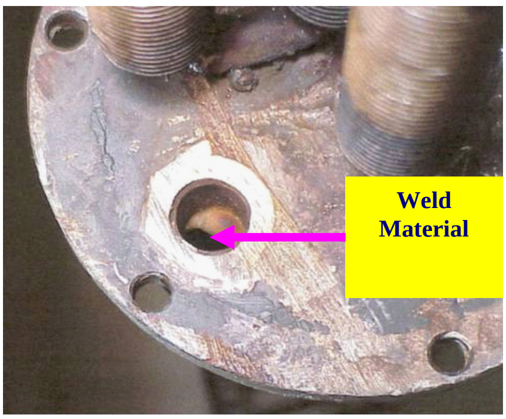

Fig. 22. Photograph showing the obstruction in the flow path at the flange due to defective welding.

Fig. 23. Photograph of pipe 2 (internal view) showing corrosion at the welding holes. Pits and cleavages can be seen.

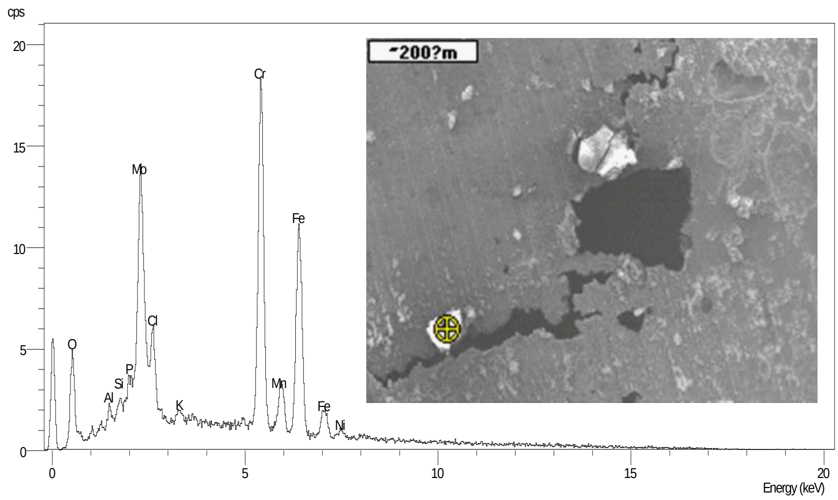

Fig. 24. SEM picture of the weld area in sample 1A shows the presence of small and big pits all over the surface. Emanation of the crack can also be seen.

corrosion in 317 SS material which resulted in the formation of pits and subsequently initiation and propagation of corrosion process (Fig. 24).

The existing weld joint, exhibited poor performance due to inadequate corrosion resistance to brine can be replaced by tig weld using Inconel 625 welding rods. The latter appeared to provide sound weld.

10. Case IX. Failure of a large water transmission steel pipeline

Leakages occurred in one of the biggest high pressure water transmission pipeline (length 467 km; diameter 1.5 m; pumping capacity 834,000 m^3/d). The steel pipelines have been in operation for more than 20 years. The pipes are internally lined with cement mortar and externally coated with polyethylene (PE).

The pipe was found ruptured at 6 o'clock positions away from the joints. The pipe was found to be severely corroded at or around the leakage point from which water was flowing out profusely (Fig. 25). The P.E. coating around the leakage appeared to be disbonded exposing the bare steel surface. The different steps involved during the failure are:

- Dismemberment of external P.E. coating left bare steel. Surface of the pipe exposed to highly corrosive soil.
- Steel in contact with corrosive soil at 6 o'clock position initiated corrosion on the external side. Subsequently, the process of corrosion propagation progressed for a long time (Fig. 26).
- The corrosion of steel pipe resulted in localized thinning of the well of the pipe and subsequent rupture of the pipe.

Fig. 25. Photograph showing gushing of the water from the leaked pipeline.

- The pits on the water side were formed near or far away from the rupture as a result of localized removal of cement lining (Fig. 27).
- These pits could act as the precursor for rupture which would occur in future at other locations.

It is recommended to rejuvenate the CP system of pipeline.

11. Case X. Shearing of a shaft in a brine recycle pump of a desalination plant

Shearing of a shaft in a brine recycle pump was reported (Fig. 28). Failure of shaft, discharge column pipe,

Fig. 26. Photograph showing close-up of the rupture site.

Fig. 27. Photograph of the inner surface of the pipe section showing presence of pits of various dimensions.

Fig. 28. Closer view of first rupture in the shaft.

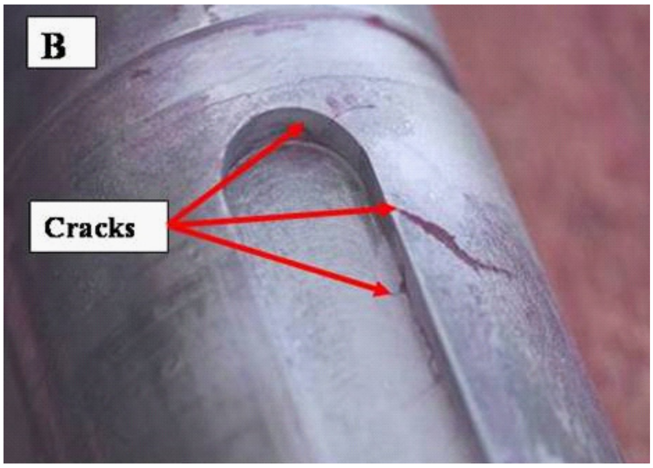

Fig. 29. Cracks location on shaft key area.

elbows and other parts of the brine recycle pumps in desalination plants have been reported from time to time. In most cases the cause of failure was originated from materials. The shaft material is usually AIS 316L and the column and elbows are made of Ni-resist, the latter have been replaced by 2205 duplex SS [UNS S31803] in many cases.

Visual inspection of the pump showed many cracks at different locations especially at the key (Fig. 29). Also some pits were found on the shaft surface. The SEM of the pit on the shaft surface shows the presence of a multi phase structure in which white particulates of non-metallic constituents (mainly Ca and Si compounds) are presumably present in a iron-rich dark grey matrix (Fig. 30). EDX analysis shows chloride ions in the pits indicating initiation of cracks in the shaft area (Fig. 30).

The corrosion would have been initiated during the operation and/or during long or short shut down. The crack initiation was located in the bearing key area which is classified as crevice. The keys are used to make the joint assembly between the shaft and coupling of the driving motor. The ingress of the chloride into the crevice of the key slot recess caused intense localized corrosion in this area giving rise to stress concentration sites for crack initiation (Fig. 31). Also, the rotational stress could have contributed in crack propagation which ultimately resulted in failure by corrosion fatigue.

The following remedial actions were recommended for preventing failure in the shaft of the brine recycle pump:

1. Remedial action should be taken for eliminating any chances of chloride ingress inside the key recess. This may require design modification of the assembly between the shaft and the coupling.

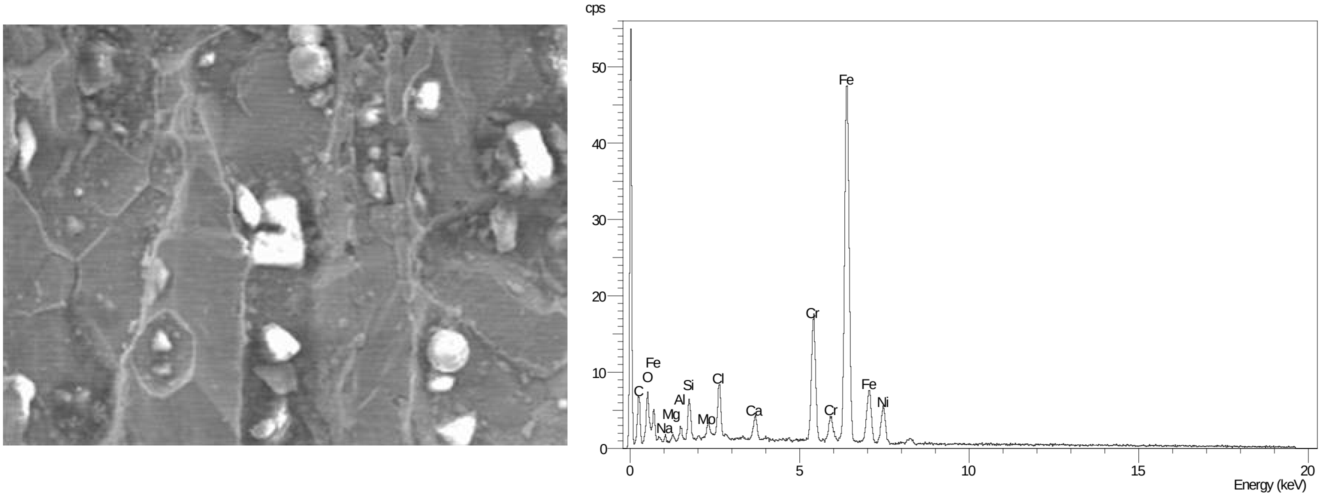

Fig. 30. EDX profile of pit on the shaft surface.

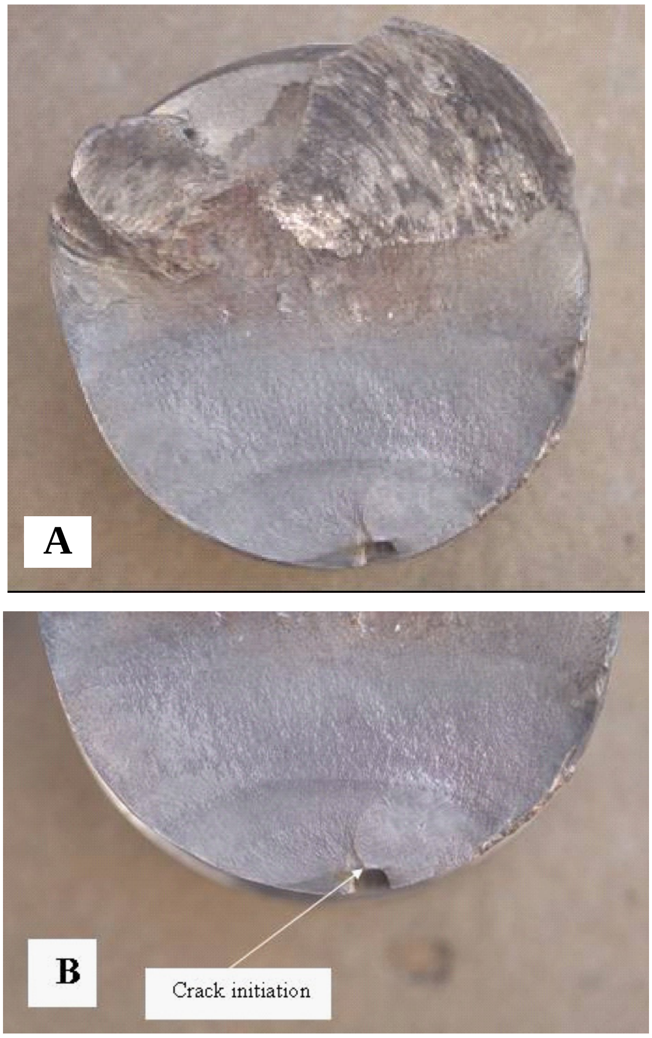

Fig. 31. Closer views (A and B) of a face of the fractured shaft.

2. All brine recycle pumps must be inspected by dye penetration test (DPT) during routine maintenance.

References

[1] M.A. Hassan and A.U. Malik, Corrosion resistant materials for seawater RO plants, Desalination, 74 (1989) 189.

[2] A.U. Malik, P.C.M. Kutty, I.N. Andijani and S.A. Al-Fozan, Material performance and failure evaluation in SWCC MSF plants, Desalination, 97 (1994) 171–187.

[3] A.U. Malik, S. Ahmed, I.N. Andijani and S.A. Al-Fozan, Corrosion behavior of steels in Gulf seawater environment, Desalination, 123 (1999) 205–213.

[4] A.U. Malik and P.C.M. Kutty, Corrosion and material selection in desalination plants, Proc. SWCC Operation and Maintenance Conf., April 27–29, 1992, p. 304.

[5] A.U. Malik, N.A. Siddiqi and I.N. Andijani, Corrosion behavior of some highly alloyed stainless steels in seawater, Desalination, 97 (1994) 189–197.

[6] B.J. Moriz and W.J. Pullock, eds., Process Industries Corrosion, NACE, Houston, Texas, 1986.

[7] A.U. Malik, P.C.M. Kutty, N.A. Siddiqi, I.N. Andijani and S. Ahmed, The influence of pH and chloride concentration on the corrosion behavior of AISI 316L steel in aqueous solutions, Corrosion Sci., 14 (1992) 1809–1827.

[8] T. Hodgkeiss, A. Maciver and P.Y. Chong, Galvanic studies related to the use in desalination plant of corrosion resistant materials, Desalination, 66 (1987) 147.

[9] W.S. Lee, J.W. Oldfield and B. Todd, Corrosion problems caused by bromine formation in additive dosed MSF materials, Desalination, 44 (1983) 209.

[10] B. Todd, Chemistry and Industry, Selection of materials for high reliability seawater handing system, 1977, p. 14.

[11] Z. Szklarska-Smialowsk, Pitting Corrosion of Metals, NACE, Houston, 1986.

[12] A.U. Malik, I.N. Andijani, A.M.T. Jamaluddin and S. Ahmed, Crevice corrosion behavior of high-alloy stainless in a SWRO pilot plant, Desalination, 171 (2004) 289–298.

[13] A.U. Malik and S. Al-Fozan, Localized corrosion of AISI 316L SS in Arabian Gulf seawater, Desalination, 97 (1994) 199–212.

[14] J.W. Oldfield and W.H. Sutton, New techniques for predicting the performance of stainless steels in seawater and other chloride-containing environments, Br. Corrosion J., 15 (1980) 31.

[15] T.S. Lee, R.M. Kain and J.W. Oldfield, The effect of environmental variables on crevice corrosion of stainless steels in seawater, Mater. Performance, 23 (1984) 9.
[16] R.M. Kain, Effect of surface finish on the crevice corrosion resistance of stainless steels in seawater and related environments, Corrosion 91, Paper 508, NACE, Houston, Texas, 1991.
[17] M. Waston and J. Postelwaite, Numerical simulation of crevice corrosion of stainless steels in nickel alloys in chloride solution, Corrosion, 46 (1990) 522.
[18] J. Olsson and H.G. Rutzner, Experience with a high alloyed stainless steels under highly corrosive conditions, Werkstoffe und Korrosion, 40 (1989) 279.
[19] H.P. Hack, Crevice corrosion behavior of molybdenum containing stainless steels in seawater, Mater. Performance, 22 (1983) 29.
[20] E.J. Kuber, Jr., Curbing Corrosion in Marine Environment Advanced Materials and Process, Metal Park, OH, USA, 1988.
[21] A.U. Malik, N.A. Siddiqi, S. Ahmed and I.N. Andijani, The effect of dominant alloys additions on the corrosion behavior of some conventional and high alloys stainless steels in seawater, Corrosion Sci., 17 (1995) 1521–1535.
[22] J.W. Oldfield and B. Todd, Environmental aspects of corrosion in MSF and RO desalination plants, Desalination, 108 (1996) 27–36.
[23] A. Al-Odwani, J. Carew, M. Al-Tabtabaei and A. Al-Hijji, Materials performance in SWRO desalination plant at KISR research and development program, Desalination, 135 (2001) 99–110.
[24] A. van Bennekom, A heat exchanger tube gets all steamed up, Eng. Failure Analysis, 8 (2001) 133.
[25] R.K. Pandey, Failure analysis of refinery tubes of overhead condenser, Eng. Failure Analysis, 13 (2006) 739–746.
[26] F. Berndt and A. van Bennekon, Pump shaft failures — A compendium of case studies, Eng. Failure Analysis, 8 (2001) 135.
[27] J.M. Kakar, A preliminary analysis of failure in gray cast iron water pipes, Eng. Failure Analysis, 7 (2000) 45–53.
[28] M. Mobin, A.U.Malik, I.N. Andijani, F. Al-Muaili and M. Al-Hajri, Failure of micron cartridge filter components in a seawater RO plant, Mater. Performance, 43(12) (2004) 53–56.
[29] M. Mobin and A.U. Malik, Premature failure of repainted epoxy on the internal bottom plate of a fuel oil tank, Mater. Performance, 44(2) (2005) 28–31.
[30] M. Mobin and A.U. Malik, Investigation of the failure of a high pressure pump motor bearing oil cooler, Mater. Performance, 44(8) (2005) 50–54.
[31] M. Mobin, A.U. Malik, I.N. Andijani, F. Al-Muaili and M. Al-Hajri, Premature water side corrosion of furnace wall tubes in high pressure boiler, Mater. Performance, 45(6) (2006) 44–49.
[32] A.U. Malik, M. Mobin, I.N. Andijani, S. Al-Fozan and A. Al-Hamad, Investigation on the corrosion of flash chamber floor plates in multistage desalination plant, J. Failure Analysis Prevention, 6(6) (2006) 17–22.