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Corrosion Failure of SS 304L Tubes- A Case Study

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ABSTRACT

This paper covers a detailed investigation to understand the failure mechanism and probable causes of tubes failure. For one heat exchanger, SS 304L tubes were ordered from an overseas tube supplier. During manufacturing of equipment, an air leak test of tube to tube sheet joints was carried out wherein leakage was detected in some of the tubes away from the tube to tube sheet joints. These tubes were removed for analysis. Failure of the tubes were analyzed through non-destructive and metallographic examinations. Multiple pits along with corrosion product were observed on tubes OD and ID. Tube failure was attributed to the combined effect of microbiologically influenced corrosion (MIC) and chloride pitting due to water contamination.

Keywords: SS 304, Tube, MIC, Chloride, Pitting

INTRODUCTION

Stainless steel straight tubes, SA 213M TP 304 were ordered for a heat exchanger from an overseas supplier. Tube details are provided below:

Tube Outer Diameter	Tube Thickness,	Total Number of Tubes	Length of tubes
19.05mm	1.65 mm	3884	16 m and 27 m

These tubes were welded with the tubesheets in the heat exchanger. As a part of the manufacturing sequence, air leak tests of tube to tubesheet joints were carried out at 1.055 kg/cm2g pressure for a minimum holding time of 10 minutes. Each individual tube to tubesheet joint was subjected to the air leak test. During the air leak test of tube to tube sheet joints, leakage was detected in two tubes. These tubes were extracted from the equipment for further examination.

Based on the examination of tubes that failed in the air leak test, it was decided to carry out eddy current test (ECT) on all other tubes along the full length to find out the extent of failure. 59 tubes showed indications in ECT either on the inside or outside surfaces. Additional tubes were extracted from the equipment for further examination.

In order to find the root cause for failure, two tubes (one tube which failed in the air leak test- tube sample 1 and other tube with indication in ECT-tube sample 2) were taken for analysis.

INVESTIGATION

Following tests were performed as part of the investigation on tube samples 1 and 2:

- Visual examination
- Chemical analysis
- Microstructure examination
- Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS)
- Sulphate Reducing Bacteria Test

VISUAL AND MACRO EXAMINATION

Tube samples were cut longitudinally in two halves for metallographic examination. Visual and macro examination was carried out on the OD as well as on the ID surfaces of the tube samples.

Tube Sample 1

The inside surface of the tube sample showed through wall cavity with irregular profile and impervious area around it. Brown coloration and localized corrosion spots were also observed on the inside surface near this through wall cavity, Figures 1a, 1c and 1d. Examination of the outside surface revealed a round hole at the location of the through wall cavity, Figure 1b.. Specimen was then cut in the transverse direction near the cavity for macro examination, Figures 1e and 1f. The cross section of the specimen was polished and examined under a stereo microscope. It showed narrow opening on ID and oval shape growth in thickness of tube (Figures 1a-f).

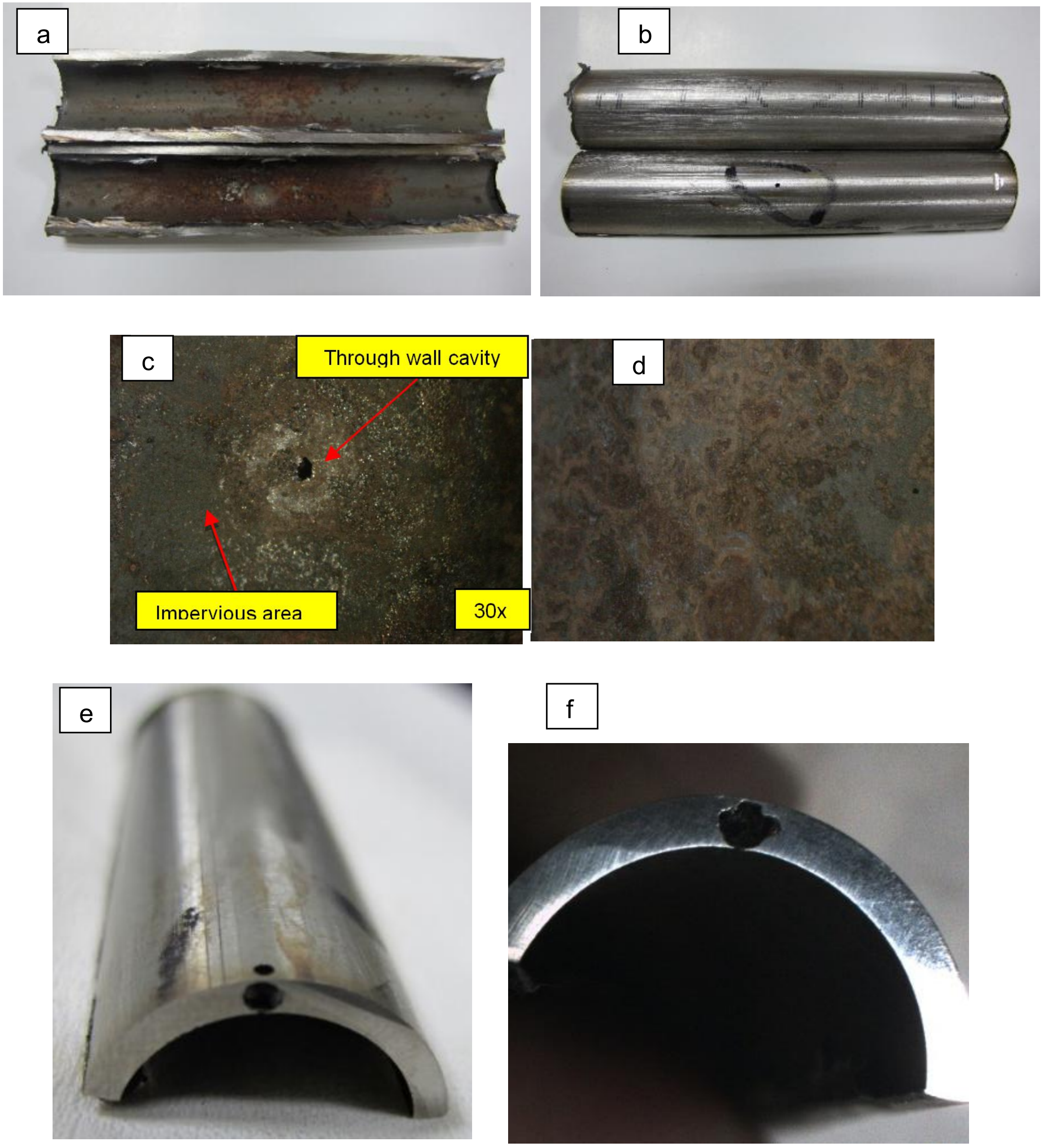


Fig. 1: (a) Inside surface (b) Outside surface (c) Cavity on inside surface (d) Corroded area near cavity (e) Cross section at cavity (f) Cross section, magnified view

Tube Sample 2

Pits along with brownish colored corrosion products were observed on the OD of the tube sample that were aligned in one orientation. No indications were observed on the ID of the tube sample. Through-wall thickness attack with oval shape growth starting from the OD was observed (Figures 2a-d).

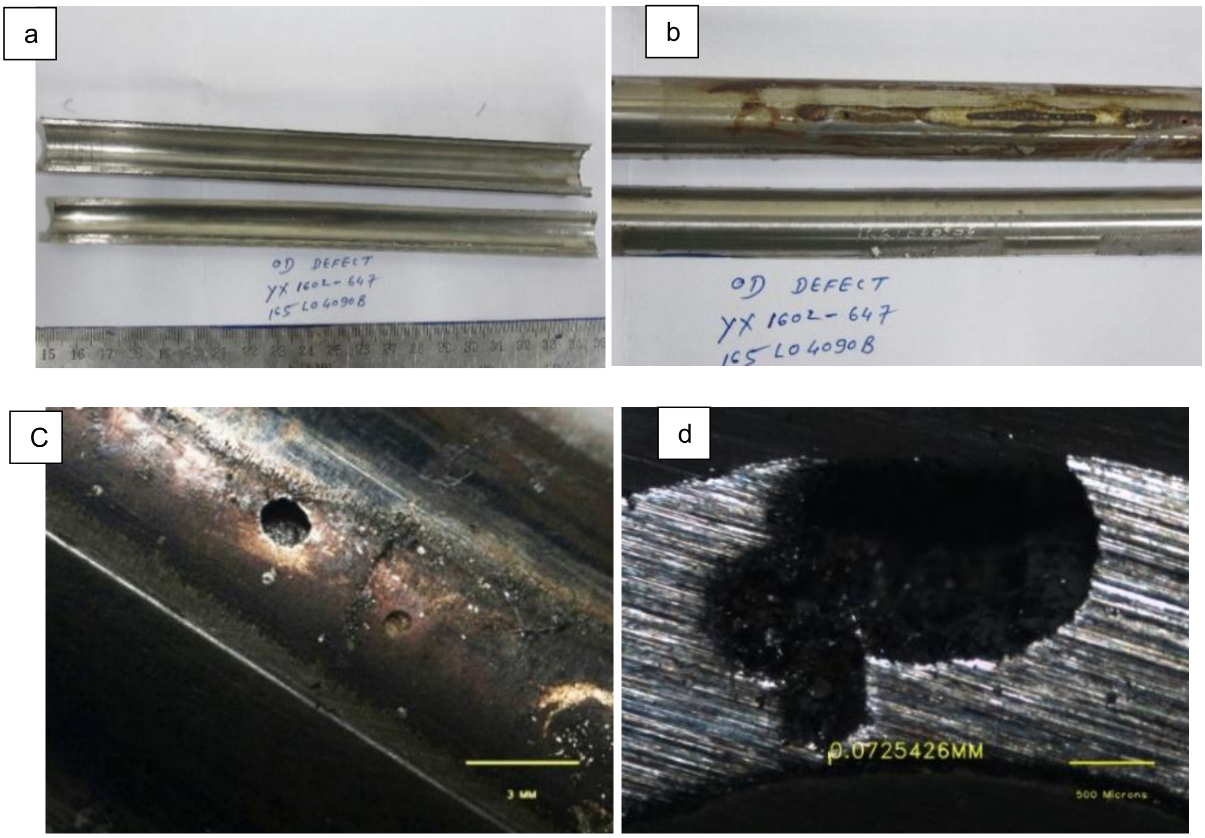


Fig. 2: (a) Inside surface (b) Outside surface (c) OD at 10X (d) cross section at 45X

CHEMICAL ANALYSIS

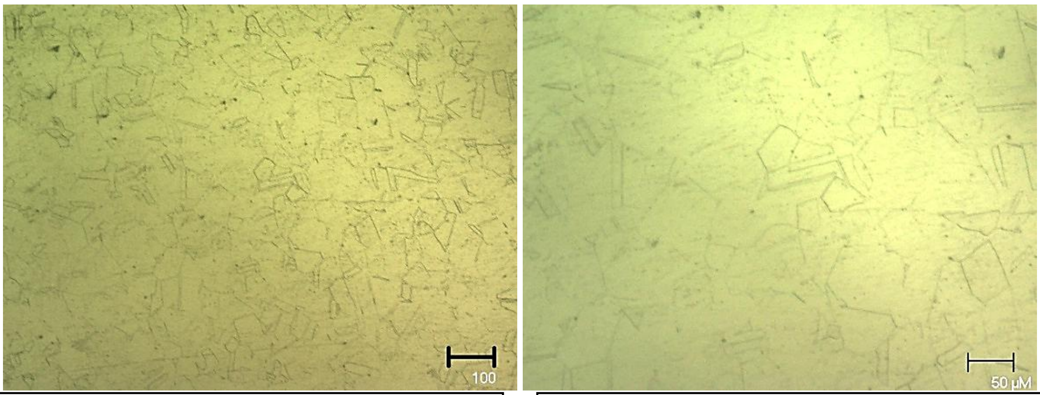
Tube samples were subjected to chemical analysis by Spectroscopy, and the results are tabulated in Table 1.

Table 1: Chemical Analysis of tube samples 1 and 2

Element	Chemical analysis of tube sample 1	Chemical analysis of tube sample 2	Material specification requirement as per SA688M in %
%C	0.025	0.27	0.08 max.
%S	0.014	0.015	0.030 max.
%P	0.026	0.024	0.045 max.
%Mn	1.5	1.6	2.0 max.
%Si	0.51	0.52	1.0 max.
%Cr	18.3	18.5	18-20
%Ni	8.08	8.07	8-11

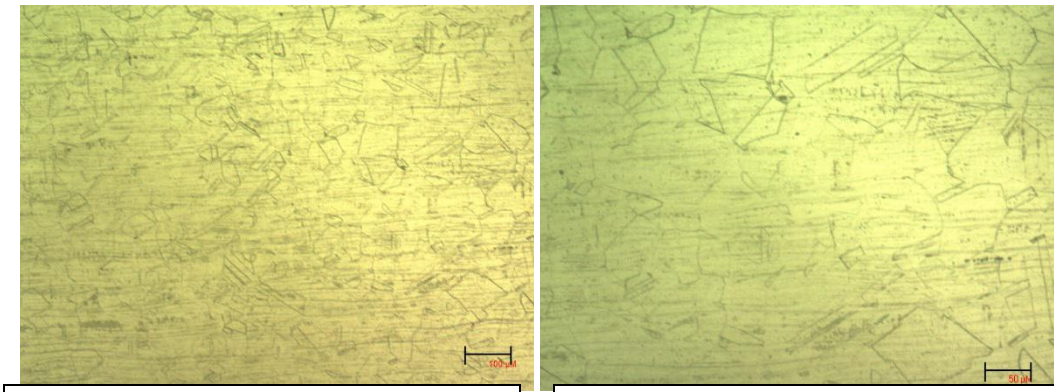
MICROSTRUCTURE EXAMINATION

Metallography examination of both the tube samples revealed a normal austenitic step structure without any carbide precipitates at grain boundaries (Figures 3 and 4)



Etchant: 10% Oxalic Acid Mag: 100X	Etchant: 10% Oxalic Acid Mag: 200X

Figure 3: Microstructure at cross section of tube sample 1



Etchant: 10% Oxalic Acid Mag: 100X	Etchant: 10% Oxalic Acid Mag: 200X

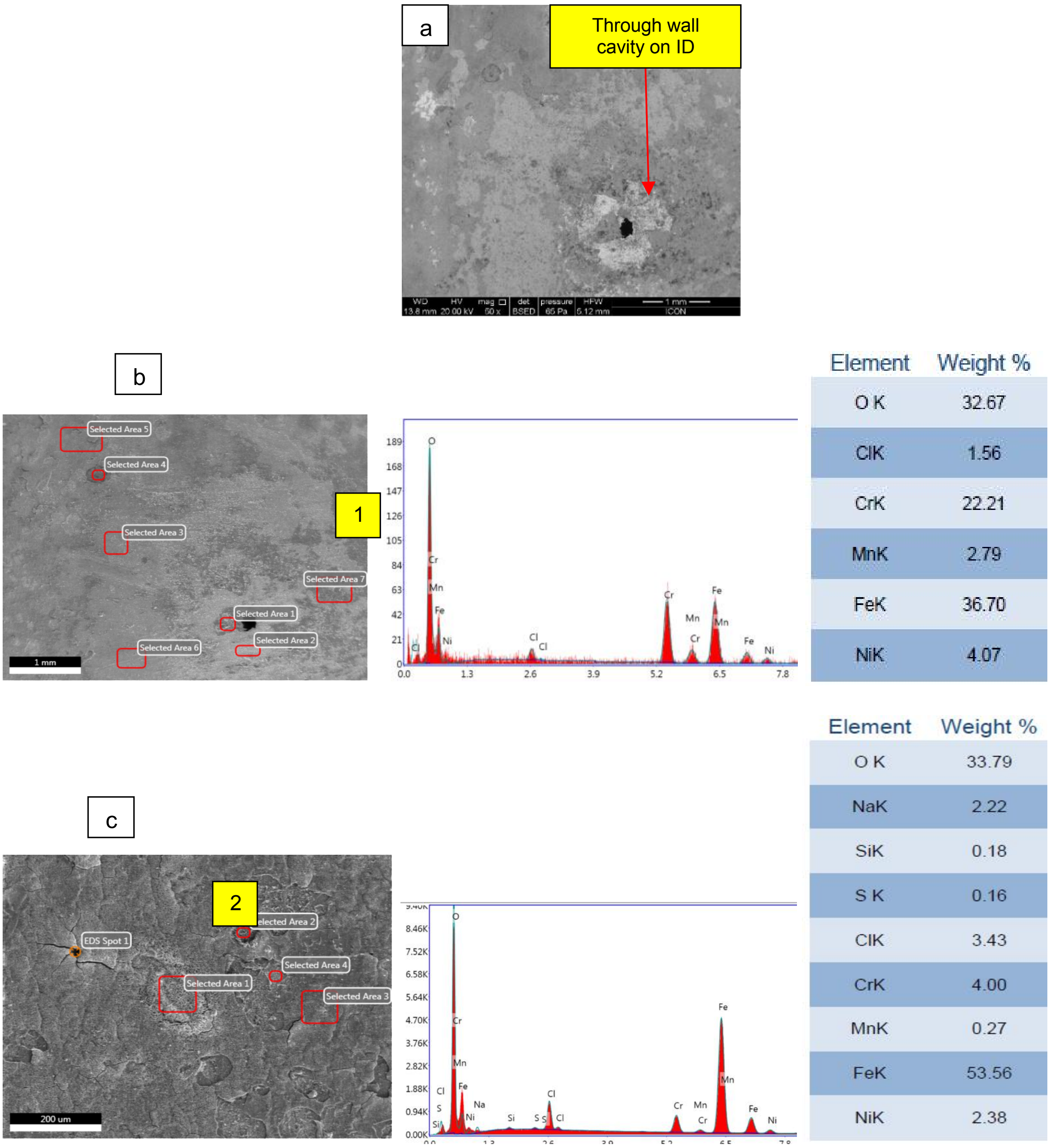
Figure 4: Microstructure at cross section of tube sample 2

SEM and EDS

SEM-EDS analysis was carried out on the samples of tubes that leaked in the air test, and tubes that showed indications in ECT.

Tube Sample 1

SEM analysis of the affected area showed few shallow cavities in addition to deep cavity observed in visual examination on the inside surface of both the tube samples. All these cavities were located in the rusted areas. EDS showed presence of chloride ions in the range of 0.89 to 3.43% and other elements like O, Ca, Mn and Na (Figures 5a-c).



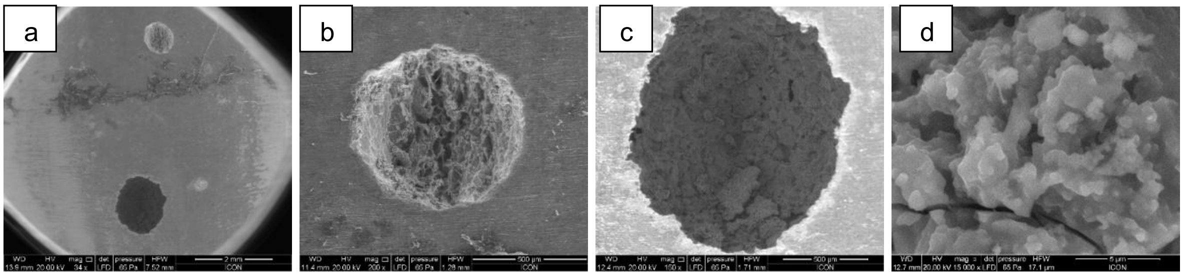
Element	Weight %
O K	32.67
ClK	1.56
CrK	22.21
MnK	2.79
FeK	36.70
NiK	4.07

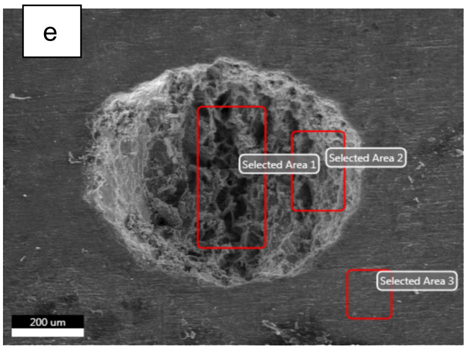
Element	Weight %
O K	33.79
NaK	2.22
SiK	0.18
S K	0.16
ClK	3.43
CrK	4.00
MnK	0.27
FeK	53.56
NiK	2.38

Fig. 5: Tube sample 1 (a) SEM image (b) EDS at location 1- Near through wall cavity (c) EDS at location 2- Inside shallow cavity

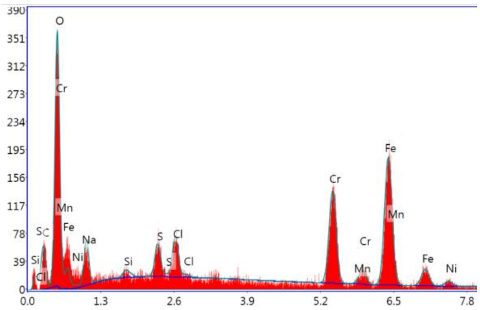
Tube Sample 2

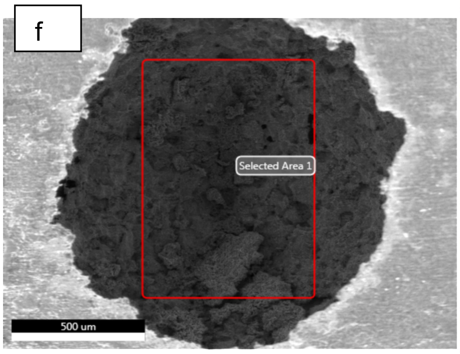
SEM analysis showed pits on the OD in both tube samples. A small cavity on the ID (opposite to one OD pit) was observed in the tube sample R21-T25. EDS on the OD surface showed presence of O, C, Cl, S, Ca and Na in the vicinity of the pit (Figures 6a-g).





Element	Weight %
C K	16.87
O K	32.55
NaK	6.98
SiK	0.34
S K	1.70
ClK	2.26
CrK	11.59
MnK	0.18
FeK	26.17
NiK	1.35





Element	Weight %
C K	11.46
O K	25.01
NaK	6.14
SiK	0.53
S K	1.67
ClK	2.44
K K	0.56
CaK	0.51
CrK	12.48
MnK	1.07
FeK	35.10
NiK	3.03

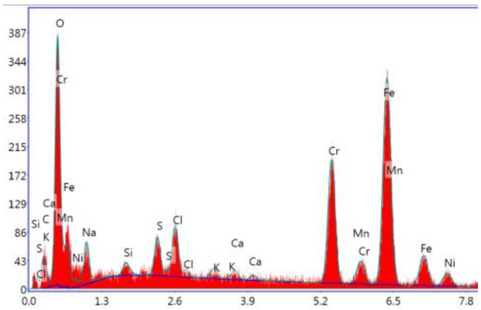
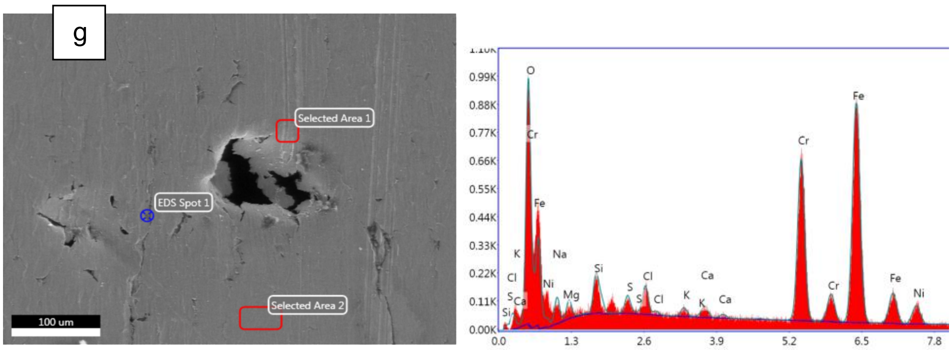


Fig. 6: (a-d) SEM Images on outside surface (e) EDS at shallow pit on outside surface (f) EDS at deep pit on outside surface



Element	Weight %
O K	20.28
NaK	4.90
MgK	2.10
SiK	2.24
S K	1.00
ClK	1.60
K K	0.56
CaK	0.76
CrK	18.53
FeK	42.88
NiK	5.16

Fig. 6 (g): EDS at small cavity on ID-opposite to OD deep pit

SULPHATE REDUCING BACTERIA (SRB) TEST

Swab samples were taken from the affected locations and tested using a portable kit (BACTASLYDE BS-115). Test results showed presence of Sulphate Reducing Bacteria which is indicated by blackening of the test solution (Figures 7a-b).

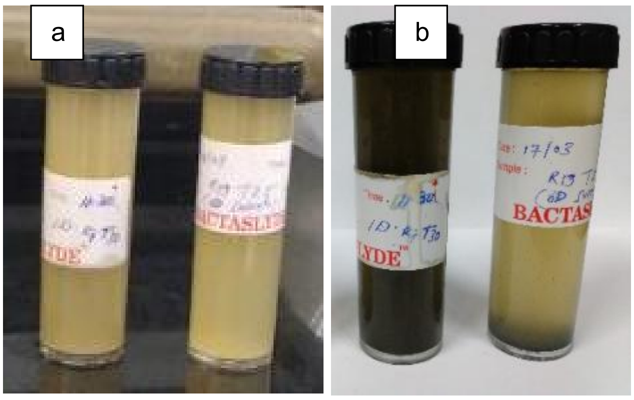


Figure 7: SRB test of tube samples (a) Day 1 (b) Day 6

RESULT AND DISCUSSION

Visual and macro examination of the inside surface of the tube sample that failed in the air leak test showed the presence of multiple pits along with brownish corrosion marks.

Visual examination of the tube samples indicated that corrosion marks on the outside surface were aligned along the tube length in one orientation. This implies that the tubes were in contact with an adjacent tube in storage or other surface that was contaminated with stagnant water for long duration, and this stagnant water most likely led to corrosion attack on the tube OD. Macro examination of the cross sections at the location of the pits on the tube OD shows that the pits initiated from the outside surface and propagated to the inside surface with minimum wall thickness remaining of about 0.07 mm. This translates into a very high thickness loss of about 1.5 mm in a few months for SS304L.

SEM of tube sample 1 which failed in the air leak test showed pits on the inside surface. SEM of tube sample 2 with indications in ECT show pits on the outside surface.

EDS analysis at the pit location on tube sample 1 showed presence of 33.79% O, 3.43% Cl and 2.22% Na. EDS analysis at the pit on tube sample 2 showed presence of 32.55% O, 2.26% Cl and 6.98% Na. The presence of high concentration of Na and Cl ions would have resulted due to contact with contaminated water containing salt. Besides Cl- ion, high content of S of 1.7% was also observed at the corrosion pits on tube sample 2 which could be due to SO4- in contaminated water. Since chlorides, sodium and sulfur ions content were observed in the affected tube samples, it is likely that saline water was in contact with the tubes.

Testing of tube samples using the SRB portable test kit confirmed presence of SRB, which corroborates with the significant amount of sulfur found in EDS analysis.

Typical morphology of corrosion attack in tubes both on ID and OD shows subsurface growth of pits through the tube thickness. Subsurface growth of the pits axially as well as along the width shows a typical tunnel pattern similar to that reported by Curtis W. Kovach [1], et al. and also by G. Kobrin et a [2]l. in one of the case studies which is attributed to MIC attack. Majid Ghahari, et al.'s experimental work showed subsurface growth of pits in width due to presence of chloride [3]. Thus the typical morphology of pits as observed on tube samples, as well as the presence of sulfur and detection of SRB suggests that the corrosion attack was a result of a combined effect of chloride pitting and MIC.

In some of the tubes, the remnant water from the original hydro test (conducted during tube manufacturing) would have remained stagnant due to an ineffective drying procedure that was noticed during the audit of the mill. This would have caused a localized increase in concentration of contaminants due to evaporation of water mainly at low lying areas of the tubes that would be prone to water accumulation and stagnation. This appears to be the likely cause of localized corrosion attack on the tubes during manufacturing at the supplier end. Corrosion failure of stainless steel components due to presence of stagnant water over a period of time has been reported by G. Kobrin [2].

Weather data for the period when the boxes were dispatched from the tube supplier and stored at a port for a few days suggest that the boxes of tubes could have been exposed to rain. Also the boxes were kept on the upper deck of the vessel during the voyage. There exists the possibility of saline water ingress due to rain, splashing into the wooden boxes as the boxes were not perfectly sealed, with the result that the tubes surfaces could remain in contact with the ingressed water for long time during transportation.

On receipt of tubes, no traces of water were observed in tube boxes. This could be due to drying of water during transportation.

CONCLUSIONS

The detailed investigation and literature study conclusively prove that the mechanism responsible for tube failure is the combined effect of Microbiologically Influenced Corrosion (MIC) and Chloride Pitting corrosion. Tubes seem to have been exposed to stagnant/ contaminated water at tube mill and/ or transit leading to this corrosion attack.

REFERENCES

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2. G. Kobrin, et al “Microbiologically Influenced Corrosion of Stainless Steels by Water Used for Cooling and Hydrostatic Testing”.
3. Majid Ghahari et al, “Synchrotron X-ray radiography studies of pitting corrosion of stainless steel: Extraction of pit propagation parameters”, Corrosion Science 100 (2015)23–35.