Root cause failure analysis of reducer weld-joint leakage for liquid outlet of slug catcher

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Root cause failure analysis of reducer weld-joint leakage for liquid outlet of slug catcher

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ABSTRACT – This paper presents a failure analysis of reducer weld-joint leakage for liquid outlet of slug catcher. The leak point was found on the area of weld joint with position relative to clock position from 9 to 3 o'clock. In order to determine morphology and mechanisms of crack were observed through laboratory tests including chemical composition test, weld macro analysis, microstructure analysis, and corrosion product analysis. Failure analysis result was found that corrosion process consumed the root weld material and cause leakage. The corrosion is occurred due to combination effect of galvanic cell, root weld microstructure, turbulence and corrosive fluids. Scaling was found based on scale analysis. Therefore the pH was indicated high enough and showed the small chance for corrosion due to carbon dioxide (CO_2). Detailed investigation also revealed that the inconsistent of weld root which resulting excessive root penetration over 3 mm. An excessive weld root about 5.6 mm is observed which was as result of improper instant repair. This profile of weld root will disrupt the flow and cause the weld root to be more anodic and vulnerable to corrosion.

1. Introduction

Investigation of piping failure is very common to be used in the oil and gas industry. Understanding the failures of piping system may help the industry to design and operate their piping system carefully. There must be several different aspects to be considered as the probability of failure of piping systems at various weld joints, branches, nozzles and piping itself. Nondestructive Testing (NDT) inspection is one of inspection method which may control and determine the condition of internal piping systems. However in some cases, piping failure due to leakage may not be detected using NDT inspection. Failure analysis and fracture investigations of surface flaw which might have undetected using NDT inspection, may not become through thickness during the components life time [1].

There are some cases which may lead the piping leakage on weld joint area. The residual stress of the elbow pipe and the heat effect of the welding process are the main problem of piping leak and contribute the cracks which may be caused by stress corrosion cracking [2]. Failure due to corrosion attack in combination with misalignment of the pipe, may lead to an accelerate corrosion rate in carbon steel API 5L grade B [3]. The premature failure on the longitudinal weld of ERW pipe also occurred due to the sediment deposits and the elevated Cl^- concentration [4].

In this case study, piping leakage was found on the area of weld joint position on spool line of slug catcher. This spool line was used to deliver two phases fluid. Previously there were also found leakage on that spool line. However, the repair had been conducted using welding technique. Therefore, in order to prevent another failure in the reducer weld joint and tee spool weld joint, the failure analysis may be conducted on the leakage point of reducer weld joint material, ASTM A 105 and ASTM A 106 Grade B, and tee spool weld joint material, ASTM A 105 and ASTM A 234.

2. Methodology

The failure analysis of reducer weld-joint leakage was investigated by testing the spool leakage in the laboratory. The laboratory tests that was carried out on the spool leakage material including chemical composition test using Optical Emission Spectrometry (OES), weld macro analysis using Optical Macroscopy, microstructure analysis using Optical Microscopy, and corrosion product analysis using X-Ray Diffraction (XRD).

2.1. Visual and Macroscopy Examination

Macroscopy examination was conducted on weld joint leakage. This examination was the next step after conducting visual examination in any metallurgical failure investigation. Both of this examination may help to identify the damage surface of material and also possible visible surface defects. Basically, both of these examination were categorized as non-destructive examination. However in some cases, macroscopy examination required polished and etched material to examine the material sample.

2.2. Chemical Composition Test

The damage or failure pipe were already determined the analyzed location for chemical composition sample. The chemical composition test was conducted in accordance with ASTM A751 and ASTM E 415. The chemical analysis was conducted at the facilities of CMPFA Company using WAS AG-Foundry Master with 8 metal base detectors including Fe, Al, Ni, Pb, Cu, Mg, Zn, Ti.

2.3. Microstructure Analysis

Scanning Electron Microscopy (SEM) was used for the metal characterization on the metal structures, as well as in fracture surfaces analyzing. Field Emission SEM was used to analysis the failure with magnification up to 500.000x of multi specimens. Utilizing of SEM may revealed the surface morphology of defects characteristics due to high resolution and field depth of SEM. Basically, using SEM was also followed by XRD analysis to detect the corrosion product.

2.4. Corrosion Product Analysis

As mention above on microstructure analysis, XRD analysis is usually used to determine corrosion product of failure sample. The XRD analysis using Philips, PW 1430 Generator to determine any corrosion products in this weld joint leakage pipe. There was a thing to note that the x-ray peak for any different elements might overlap.

3. Results and Discussion

3.1. Visual Examination Result

Visual examination was performed on the spool material after sectioning. The sectioning of spool material is made in order to observe the internal surface of the spool material. Examination is made by unaided eyes. The visual examination of the reducer 4”x2” may be shown Figure 1, 2, and 3, respectively.

Based on internal view of the spool reducer R.W #1 and R.W#2, they were suggested that the corrosion product found on the top surface area. The color was nearly dark brown, very crumble and also easily wiped away. However, generally the layer of scale and corrosion product was mainly found on the bottom surface of reducer. The combination of color was dark brown and earth yellow. The corrosion product was very hard and sticks onto the steel surface. The erosion marks are not observable in the internal of reducer and on the both flange mouth, inlet and outlet mouth.

Visual examination also performed on Tee-Weld 4” spool. The internal view of tee-weld 4” may be shown in Figure 4. The appearance of corrosion product and layer of scale were found on the bottom surface of tee. The characteristic and combination color were similar with layer found in the reducer

Figure 1. Internal view of R.W #1

Figure 2. Internal view of R.W #2

Figure 3. Internal view of R.W #3

Figure 5 and 6 shows that there were weld root degradation indications on weld joint of T.W#4 and T.W#5. The weld root degradation may be resulted either from improper of welding technique or improper instant repair. This weld root degradation may cause the turbulent flow of fluid in the weld-joint pipe and also may cause the root weld more anodic and vulnerable to corrosion. However, the corrosion product were found on the 2" straight pipe with dark brown of its color. Based on its fluid service and the visual result, the corrosion product may be siderite ($FeCO_3$). XRD analysis may show the dominant corrosion product in the straight pipe.

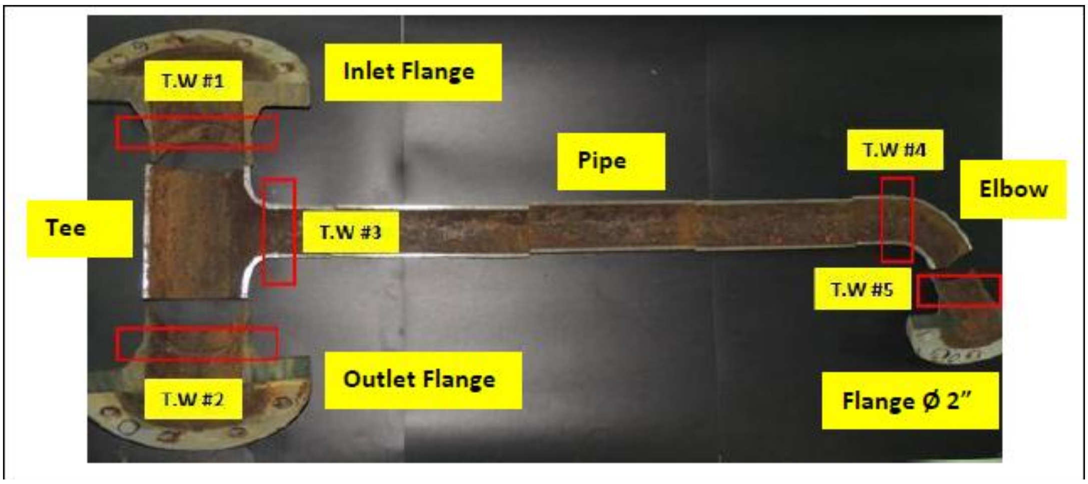


Figure 4. Internal view of Tee 4"

Figure 5. Internal view of T.W#4

Figure 6. Internal view of T.W#5

3.2. Chemical Composition Result

The chemical composition test was already conducted on the pipe spool, weld metal spool, inlet and outlet flange. The chemical composition of the flanges and reducer body conformed to the material specification as shown in Table 1. Each of joint weld metal chemical composition was shown in Table 2. There was no significant difference in the chemical composition, therefore the chemical composition of reducer and reducer weld joint are still normal.

The chemical composition test results of tee spool and tee spool weld joint may also be shown in Table 3 and Table 4. The results also found that there was no significant difference in the chemical composition, therefore the chemical composition of tee spool and tee spool weld joint are still normal.

Table 1. Chemical composition test results of reducer

Part	C (%)	Mn (%)	Si (%)	P (%)	S (%)
Inlet Flange Ø 4”	0.18	1.15	0.26	0.009	0.007
Outlet Flange Ø 2”	0.19	1.17	0.24	0.007	0.004
ASTM A 105	**0.35 max**	**0.60-1.05**	**0.10-0.35**	**0.035 max**	**0.040 max**
Reducer Body Ø 4”	0.20	0.64	0.21	0.015	0.009
ASTM A106 Grade B	**0.30 max**	**0.29-1.06**	**0.10 min**	**0.035 max**	**0.035 max**

Table 2. Chemical composition test results of reducer weld joint

Part	C (%)	Mn (%)	Si (%)	P (%)	S (%)
R W1	0.086	1.44	0.72	0.010	0.006
R W2	0.087	1.46	0.75	0.009	0.006
R W3	0.100	1.47	0.71	0.009	0.006

Table 3. Chemical composition test results of tee spool

Part	C (%)	Mn (%)	Si (%)	P (%)	S (%)
Inlet Flange Ø 4”	0.19	1.20	0.24	0.007	0.003
Outlet Flange Ø 4”	0.16	1.23	0.19	0.008	0.006
Outlet Flange Ø 2”	0.18	1.12	0.16	<0.003	0.011
ASTM A 105	**0.35 max**	**0.60-1.05**	**0.10-0.35**	**0.035 max**	**0.040 max**
Elbow Ø 2”	0.16	0.78	0.20	0.012	0.005
Tee Ø 4”	0.20	0.66	0.21	0.023	0.009
ASTM A 234	**0.30 max**	**0.29-1.06**	**0.10 min**	**0.05 max**	**0.058 max**
Pipe Ø 2”	0.19	1.03	0.17	0.012	0.009

ASTM A106 Grade B	**0.30 max**	**0.29-1.06**	**0.10 min**	**0.035 max**	**0.035 max**

Table 4. Chemical composition test results of tee spool weld joint

Part	C (%)	Mn (%)	Si (%)	P (%)	S (%)
TS W1	0.094	1.40	0.66	0.010	0.007
TS W2	0.087	1.30	0.59	0.009	0.006
TS W3	0.089	1.37	0.65	0.009	0.005
TS W4	0.112	1.32	0.59	0.010	0.006
TS W5	0.095	1.22	0.59	0.010	0.008

3.3. Weld Macro Result

Macrophotography test was conducted on the weld joint spool. Samples are cut from spool material. Its cross section is prepared with the following steps such as grinding, polishing and etching. Figure 7 shows macrophotograph result of weld joints on reducer 4"x2". Based on Figure 7, there is no abnormal weld root on weld joint reducer 4"x2". The weld root height was found about 2.5 mm on each sample. However, Figure 8 shows the excessive weld root on T.W#2. The excessive root of T.W#2 may be caused by the improper instant repair. This excessive weld root may disrupt the fluid flow inside the pipe and increasing the preferential weld corrosion occurred. The preferential weld corrosion may be influenced by several parameters including flow conditions, scaling effects, the environment, steel composition and also welding procedure [5].

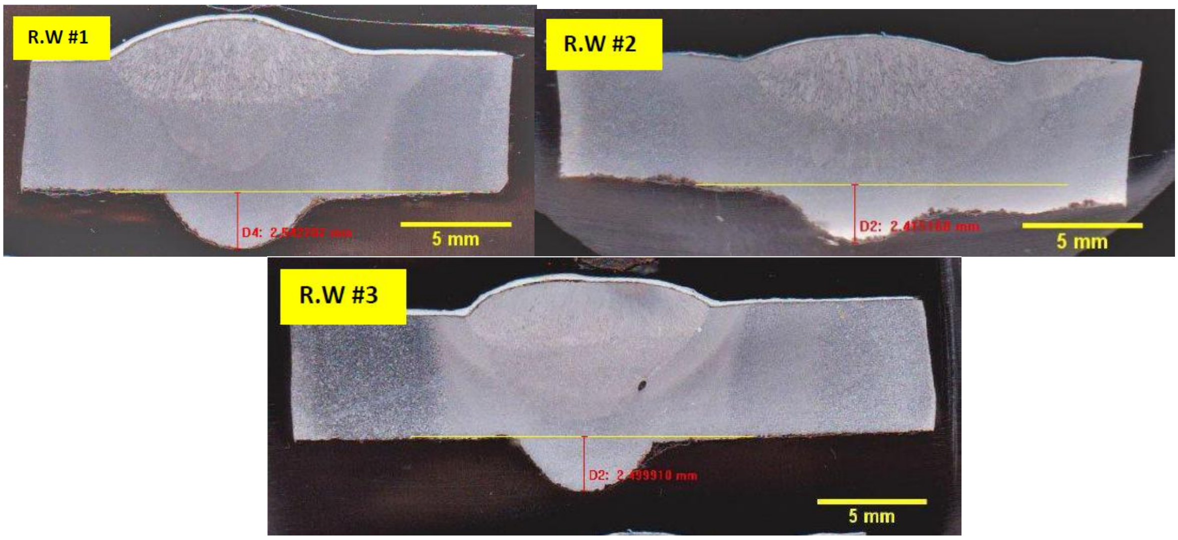


Figure 7. Macrophotograph of weld joints on reducer 4" x 2"

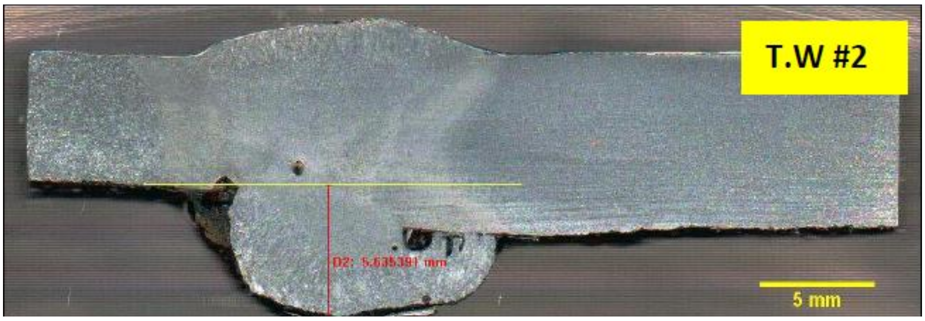


Figure 8. Macrophotograph of tee weld joints on spool 4" x 2"

3.4. Microstructure Result

The analysis of microstructure was performed on the sample after weld macro analysis has been conducted. Microstructure analysis was conducted using optical microscope with magnification of 500x. Detail observation and photography was made on specific area on the cross section of sample. The microstructure of each weld joints was found normal. There was also no detrimental microstructure on the weld joint such as martensite.

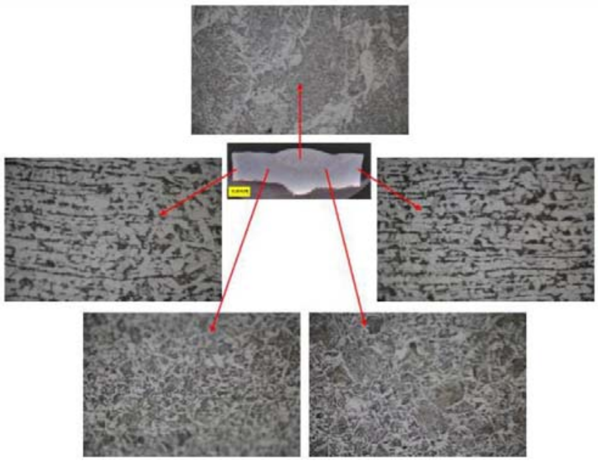


Figure 9. Microphotograph of weld joint R.W#2

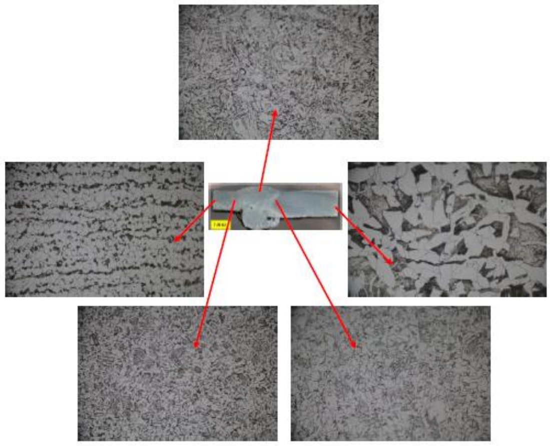


Figure 10. Microphotograph of weld joint T.W#2

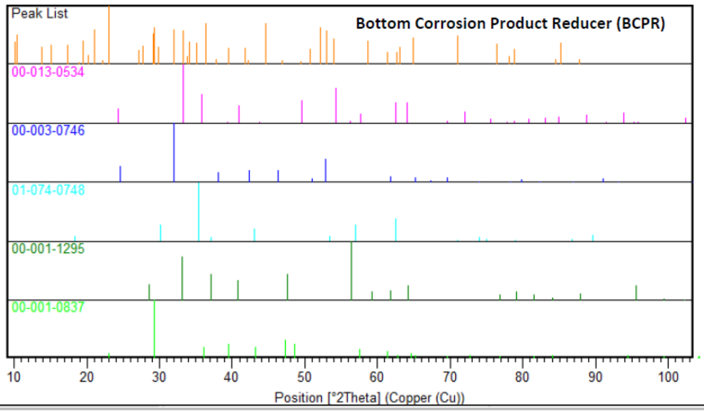
Figure 9 shows the macrophotograph of weld joint R.W#2. The microstructure analysis was taken on HAZ area. There was no abnormal microstructure on R.W#2. The combination of ferrite and pearlite was found normal on each sampling analysis. The excessive root sampling of T.W#2 was also observed on Figure 10. However, the microstructure was also found normal and there was no detrimental microstructure. Therefore, failure due to microstructure may be negligible.

3.5. Corrosion Product Result

In order to determine the compound of corrosion product in the internal surface of both reducer 4” x 2” and tee 4”, X-Ray Diffraction (XRD) was used to analyze it. There are four sampling point that was taken in the internal surface of pipe spool. Table 5 shows the description of the sample point for XRD analysis.

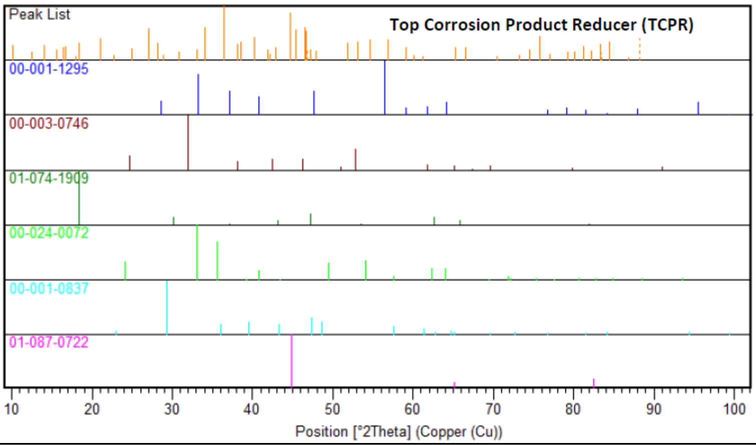
Table 5. Code description of corrosion product analysis

Code	Description
Bottom Corrosion Product Reducer (BCPR)	Sample taken from layer of scale and corrosion products with combination color of dark brown and earth yellow in reducer
Top Corrosion Product Reducer (TCPR)	Sample taken from dark brown and crumble corrosion product in reducer
Bottom Corrosion Product Tee (BCPT)	Sample taken from layer of scale and corrosion products with combination color of dark brown and earth yellow in tee
Top Corrosion Product Tee (TCPT)	Sample taken from dark brown and crumble corrosion product in tee



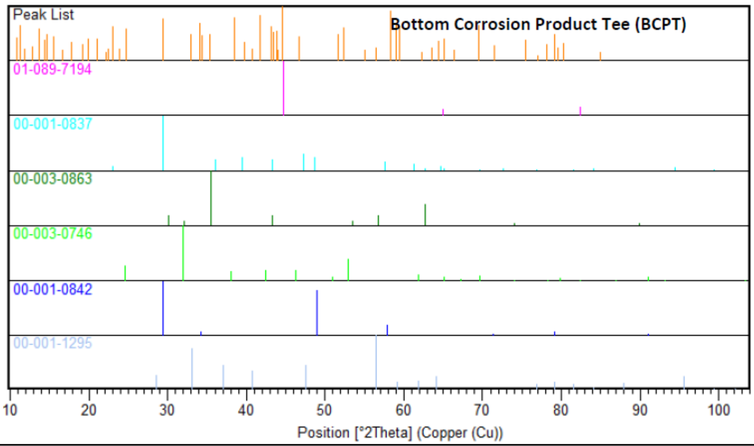
	Visible	Ref. Code	Compound Name	Chemical Formula	Score
1	✔	00-013-0534	Hematite, syn	Fe2 O3	2
2	✔	00-003-0746	Siderite	Fe C O3	4
3	✔	01-074-0748	Iron diiron(III) oxide	Fe3 O4	1
4	✔	00-001-1295	Pyrite	Fe S2	1
5	✔	00-001-0837	Calcite	Ca C O3	5

Figure 11. XRD of BCPR



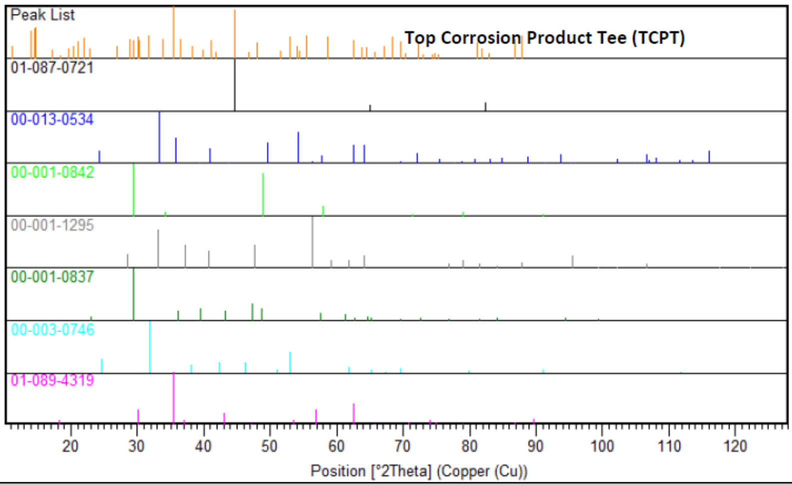
	Visible	Ref. Code	Compound Name	Chemical Formula	Score
1	✔	00-001-1295	Pyrite	Fe S2	Unmatched Strong
2	✔	00-003-0746	Siderite	Fe C O3	1
3	✔	01-074-1909	Iron diiron(III) oxide	Fe3 O4	5
4	✔	00-024-0072	Hematite	Fe2 O3	1
5	✔	00-001-0837	Calcite	Ca C O3	1
6	✔	01-087-0722	Iron	Fe	8

Figure 12. XRD of TCPR



	Visible	Ref. Code	Compound Name	Chemical Formula	Score
1	✔	01-089-7194	Iron	Fe	12
2	✔	00-001-0837	Calcite	Ca C O3	3
3	✔	00-003-0863	Magnetite	Fe3 O4	2
4	✔	00-003-0746	Siderite	Fe C O3	1
5	✔	00-001-0842	Chalcopyrite	Cu Fe S2	3
6	✔	00-001-1295	Pyrite	Fe S2	Unmatched Strong

Figure 13. XRD of BCPT



	Visible	Ref. Code	Compound Name	Chemical Formula	Score
1	✔	01-087-0721	Iron - $-alpha	Fe	18
2	✔	00-013-0534	Hematite, syn	Fe2 O3	1
3	✔	00-001-0842	Chalcopyrite	Cu Fe S2	4
4	✔	00-001-1295	Pyrite	Fe S2	Unmatched Strong
5	✔	00-001-0837	Calcite	Ca C O3	2
6	✔	00-003-0746	Siderite	Fe C O3	2
7	✔	01-089-4319	Iron diiron(III) oxide	Fe3 O4	9

Figure 14. XRD of TCPT

Table 6. Summary of XRD test

Code	Corrosion Product Findings	Indications
BCPR	Fe_2O_3, $FeCO_3$, Fe_3O_4, FeS_2, $CaCO_3$	Corrosion of steel by water, Carbonate scale, Bacterial corrosion, Sweet corrosion
TCPR	$FeCO_3$, Fe_3O_4, Fe_2O_3, $CaCO_3$, Fe	Corrosion of steel by water, Carbonate scale, Sweet corrosion
BCPR	Fe, $CaCO_3$, Fe_3O_4, $FeCO_3$, $CuFeS_2$	Corrosion of steel by water, Carbonate scale, Sweet corrosion

TCPR	Fe, Fe_2O_3, $CuFeS_2$, $CaCO_3$, $FeCO_3$, Fe_3O_4	Corrosion of steel by water, Carbonate scale, Sweet corrosion

Corrosion products may be shown from Figure 11 to Figure 14. Table 6 shows summary of XRD test of BCPR, TCPR, BCPR, and TCPR. Generally, corrosion products that occurred based on XRD tests may be caused by carbonate scale, bacterial corrosion, sweet corrosion and corrosion of steel by water. There was also presence of pyrite (FeS_2) in the corrosion product. However, it may not be considered due to the reading from XRD spectrum showed "unmatched strong". Therefore, FeS_2 may not exist in the corrosion product.

3.6. Discussions

Visual inspection revealed that there was scale formation in the internal spool pipe and reducer. Based on scale analysis, it contains calcite ($CaCO_3$) and siderite ($FeCO_3$) as majoring compounds. Calcite is the scaling product which may be predicted by the Langelier Saturation Index (LSI). Failure of the calcite may occur when the calcite layer develop the internal stress larger than the adhesive bonds [6]. According to XRD analysis, the environment is supporting to form a protective scale in the form of calcite. However, the detection of siderite in the scale is revealed that the environment is also corrosive. Siderite is the commonly product of sweet corrosion due to dissolve CO_2 gas into the water. Table 6 also shows that there are another compounds in the scale collected. There are two corrosion products from the result of steel corroded by oxygen which are magnetite (Fe_3O_4) and hematite (Fe_2O_3). Both corrosion products may be dominated by oxygen reaction due to the pH was probably high (pH=8). The suspect of microbial induced corrosion may not be proved since no evidence in the corrosion product after XRD test. The presence of FeS_2 is unmatched with the peak database of compound.

The preferential attack occurred and cause the leakage due to the weld root is more vulnerable to deterioration. The combination of flow, corrosion and weldment are the potential source of this problem since the leakages was found at the flow pattern change area. The flow pattern may change from laminar into turbulent since the protruding weld root occurred in the internal surface of spool pipe. The key influence of corrosion under turbulent flow regimes was the surface conditions formed during pre-corrosion [7]. Then, the corrosion attacks the exposed metal since the turbulent flow break the film layer. According to previous failure history, both of spool pipe and reducer had a leakage history on the 9 to 3 o'clock position. However, it has been repaired by welding technique. Therefore, the evidence of leakage may not be retrieved. It was only reported that a preferential weld attack occurred on the root weld since there was combination of flow and corrosion. The unstable condition of film layer was selectively disrupted on the weld metal then may cause the preferential weld corrosion in the pipe surface [8].

According to the weldment quality, the cross sectional of a weld is generally proportional to the amount of heat input. In multi-pass welding, the portion of previous weld pass is refined since the heat from each pass tempers the weld bead. A decreasing level of microstructure refinement of the root by the subsequent passes is the one of some factors which may increase preferential weld metal corrosion attack at weldment[9]. The root is observed to be the first pass that has undergone grain refinement due to multiple pass heating. The combination of fine root grains, turbulence of flow-induced, and the fluids, may increase the corrosion process on the weldment. The scale, which may be produced by the service fluids, at the root weld are easily damaged and corroded since the influence of high shear stress, flow regimes and fine grains in the weldment area.

Figure 11 and Figure 12 also shows that some weld roots are still in acceptable height for excessive root penetration according to BS EN ISO 5817. The average height are still below 3 mm on each sample of reducer and tee spool. However, T.W #2 is the only one sample which is measured about 5.6 mm. The T.W #2 sample is suspected as product of repair process which made on tee spool. This type of excessive weld root will abruptly change the flow pattern inside the spool tee and may lead to erosion or corrosion of the weld joint.

4. Conclusions and Recommendations

The corrosion process consumed the root weld material and may cause leakage. The corrosion process may be occurred since combination effect of galvanic cell, root weld microstructure, turbulence and corrosive fluids. According to scale analysis, presence of scale shows the high pH and gives the small probability of CO_2 corrosion damage to occur. In a range condition of pH 5.5-6.5 at temperature of 55 ^oC, there will be no corrosion product of CO_2 corrosion formed on the steel surface [10]. In other hand, according to microstructure aspect, the root weld has fine grains. It was the result of multiple pass with high input. The evidence of high heat input was shown by wide bead of the weldment. An excessive weld root about 5.6 mm has been observed and resulting the improper of instant repair process. The weld root profile will disrupt the flow and may cause the weld root to be more anodic and vulnerable to corrosion.

In order to minimize the inconsistency of weld joint quality and the improper of welding process, it is recommended to check the remaining weld joint and replace any joint with improper weld profile which may affect the flow pattern and threats such as flow accelerated corrosion.

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