A case study: Failure analysis of crude oil pipeline rupture

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Abstract: *A cross-country crude oil pipeline section of 18" diameter API 5 LX 65, LSAW of 996 km was ruptured during its operation. This pipeline is used for carrying the crude oil from an offshore tank farm to a land-locked refinery. The failure occurred along the longitudinal seam. The affected pipeline section length was 206 km. The pipeline section was in operation since a 2002 and failure reported in 2017 i.e. more than 15 years of operation. This pipeline is laid as two parallel strings of 18" diameter pipelines. Prior to failure about two years back the pipeline was inspected using Axial MFL technology based intelligent pigging survey. However, no significant corrosion or other defect was identified in ILI findings in the section which would have eventually failed. Pipeline failed from its longitudinal seam, failure initiated from HAZ when the pipeline was in operation. The failure occurred much below the MAOP of the Pipeline. The MAOP is 91.4 kg/cm² where the pipeline was operational at 77 Kg/cm². Failure appeared to be fish mouth type of failure. Pipeline failure was examined from an operational as well as metallurgical perspective.*

Key Words: Pipeline Failure, Inline Inspection, Fracture, Fatigue

1. INTRODUCTION AND PROBLEM FACED

One of the land-locked refineries of India is fed through a crude oil pipeline originating from a coastal location. The pipeline was laid as two parallel strings of 18 inch API -5 LX 65, 0.25" LSAW, termed as mainline and loopline. The mainline was constructed in 1999 and subsequently, the loopline was laid to augment its capacity in several stages. The pipeline was designed and constructed as per various codes & standards [1] [2].The configuration in the form of the schematic is shown in figure 1.

The pipeline was externally coated using DFBE (Double Fusion Bonded Epoxy) coating and impressed current based cathodic protection system was adopted as supplementary protection. Besides capturing the Pipe to Soil Potential fortnightly, various coating surveys like closed internal potential survey and direct current voltage gradient are carried out periodically to assess coating condition. Moreover, the pipeline is piggable, hence periodic cleaning of the pipeline was carried out. During these cleaning activities, pig residues were received in little quantity and analysis of pig residue indicated as such no significant component of Fe. The inline inspection (ILI) survey was also carried out about two years before failure. The survey indicated no appreciated defect at the failure point. The survey indicated 5 minor anomalies designated as internal pits were present the failed pipe between 11 – 18 %. The metal loss of such magnitude is not considered harmful as per ASME B31G. [3] The survey was undertaken in the year 2015. It is pertinent to mention that ILI was done using Axial Magnetic Flux Leakage tool, which incapable of detecting small/microcracks on weld seam or in HAZ. So if the micro or small cracks were present near weld seam, the tool was not capable of detecting the same.

The pipeline was having normal parameter operated (pressure) at 77 Kg/ cm² against its MAOP of 91.4 Kg/ cm², at the time of failure. The pressure profile indicated that approximately 72.8 kg/cm² pressure at the affected point. Suddenly the upstream pump of the pipeline tripped in a low suction simultaneously drastic increase in the volumetric flow was noticed indicating the rupture of the pipeline. Soon the confirmation was received from the field where spillage of the crude oil has taken place, due to the pipeline rupture.

1.1 Operation Observation:

Table 1: Salient Features of the pipeline:

Len[km]	Dia [in]	Grade	Seam Type	MAOP [kg/cm²]	Thickness[in]	Linefill [m³]
498	18	API5L X-65	LSAW	91.4	0.25	155660

1.2 Brief on Incidence:

The pipeline operating was being operated as the configuration is as shown in figure 1. The Pipeline in section-1 was being operated through both of the parallel pipelines. However, due to some maintenance activity, the pipeline was operated through a single pipeline in section 2. Every station is equipped with 2 motor-driven centrifugal pumps. After a continued uninterrupted operation, centrifugal pumps at station-1 tripped in the low suction. The flow rate increased in loopline in section-1 even after the pumps have tripped. This is a typical indication of a pipeline rupture. Pipeline section failed around 12 km downstream from station 1.

1.3 Recent Survey Observations:

Regular pipe to soil potential (PSP) survey was carried out as a preliminary response to a failure of the CP system or coating damages at large scale. The PSP confirmed that the

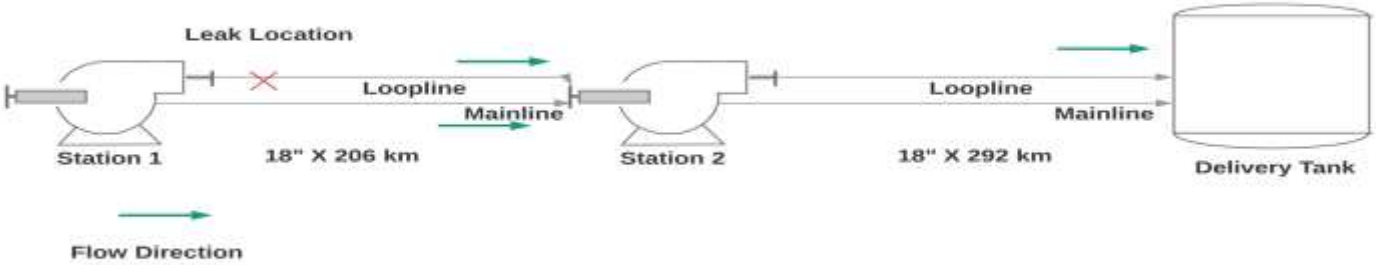

Figure 1: Operational Configuration of the pipeline during failure

Pipe was above protection level and hence couldn't be attributed to the failure of the pipeline.

As part of integrity assessment program, Inline inspection tool is considered to give the photograph of the pipeline. An axial Magnetic Flux Leakage based inline inspection survey was carried out recently before the failure. Small patches of corrosion were present in the pipeline but not near the vicinity of the pipeline. Moreover, the corrosion patches were evaluated as per ASME B31G. [3] The pipeline corrosion defects are marked as in figure no. 2.

Further to above, a dent was also located in the pipeline, which was near the leak site. However, the dent was repaired recently. Moreover, no other anomaly was reported near the failure location which may seriously pose a threat to pipeline integrity.

DCVG survey of the pipeline was also carried out in a period of a year prior to failure. No significant defect was reported near the failure location.

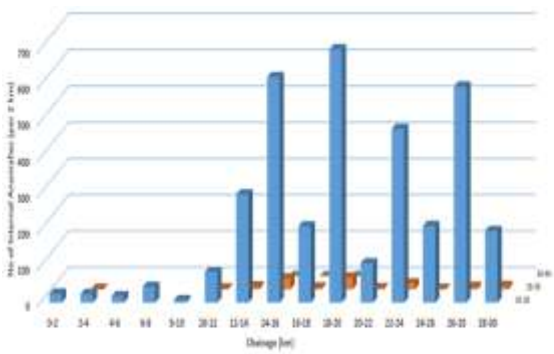

Figure 2: Corrosion anomalies distribution with chainage

Current attenuation survey yielded similar results and failed to predict the chances of external corrosion or external cracking related to corrosion.

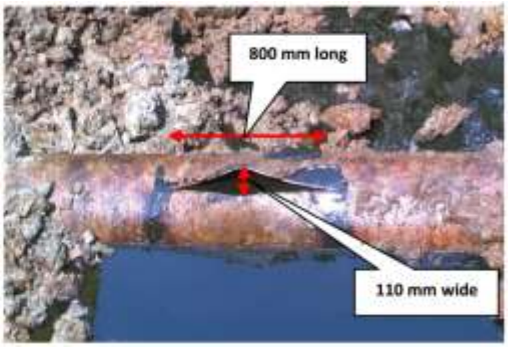

Figure 3a: Preliminary failure photographs at site

Figure 3b: Preliminary failure photographs at site

1.4 Site Investigation and inferences

After isolation of the affected section, excavation & collection of crude oil from the leaked site, the pipeline was exposed. The seam opening was to the extent of 800 mm in length and the center opening was 110 mm wide, bearing a concave curvature of pipe wall at the center resembling a fish mouth. No scales, dents or laminations were observed in the internal or external surface of the failed section. No internal or external corrosion was noticed near the failure zone. Moreover, no corrosion on seam was observed in the pipeline. Pipeline section had not shown any sign of necking or thinning near the rupture area.

A small amount of swelling was noticed near the surface. Rupture spanned over 800 mm along the pipeline longitudinal seam. The failed pipeline section is represented as figure 3.

Separation line of the fractured surface in the middle span was 100 mm & the surface was shiny and uniform. On both side of the middle was rough, fibrous and its edges had ridges with a chevron pattern.

On closer examination, it was found that in the entire 800 mm span of the fractured surface, the middle concave profiled 100mm span of opening had shiny and plain surface whereas the rest of the portion bears a fibrous and uneven surface implying that the pipe yield originated in this 100 mm span and the balance portion on either side had ductile failure resulted due to propagation of failed line along the edge of the weld seam, during the release of line pipe pressure

Figure 4a: Rupture at longitudinal pipe seam

The 100 mm long portion of the ruptured surface in the middle of the entire 800mm long failed span from where failure originated can be clearly seen to bear layer or a band-like marks implying advancement of a crack which enlarged over time **(**Figure:3**).** The crack propagation might have stopped intermittently when the pipeline was operated at lower pressures.

A top view of the portion from where failure originated, shows that the line of separation is within the weld seam (Figure-4). This also implies that the failure originated from the weld seam itself.

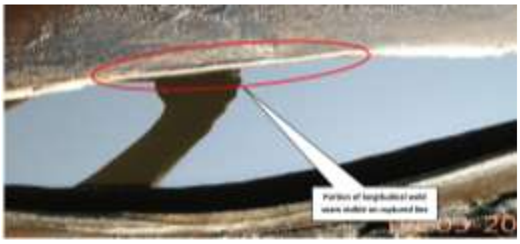

Figure 4b: Visible ruptured line

The shiny surface with the plane contour on the surface is indicative that the pipe seam weld was affected by fatigue and that the failure might have initiated from a crack/cracklike feature developed at the internal surface of the pipe from some kind of weld anomaly. Since the failure was now known to have originated from the weld seam, it can, therefore, be concluded that such an imperfection might have been present in the weld seam since the beginning.

The acute angle edge on the surface of this portion suggests ductile failure propagation with secondary microcracks forming a saw-tooth-like ridges pointing back to the origin.

Fatigue crack growth in longitudinal seams as a result of pressure cycles has been experienced only in a subset of liquid products pipelines in which the pipe was affected by certain species of seam defect conditions, and the lines operated with relatively intensive pressure cycles. The initial flaws are artifacts of the manufacturing process that escaped detection by the inspection process in the pipe mill and that were also small enough to pass the hydrostatic test at the mill or in the field prior to commissioning

Anomalous featured propagated longitudinally as well as laterally until the remaining pipe wall became alarmingly thin and inadequate to bear the line pressure

A fresh look at the section of pipe wall where failure originated reveals that all along the thickness, the color of each band though was different but the shades didn't differ much. In other words, the shade of the innermost band or layer is not very much dark compared to the succeeding layers implying that the crack might have originated in service and being in contact with oil/crude, no rust like dark patch could form. Had there been a very dark shade on the innermost layer from where crack initiated, it could have implied that the crack has originated even before the line pipe was commissioned; may be during transit or loading / unloading or stacking

Fatigue may occur in three sequential stages, the formation of a crack, called initiation, the stable incremental enlargement of the crack in service called propagation and the rapid unstable fracture. Initiation of fatigue occurs at microstructure-scale nucleation sites within the material such as inclusions or pores or lack of fusion. The presence of macro-scale stress concentrators enhance crack nucleation [4]. The fatigue strength or endurance limit is generally defined as the value for failure after a specified high – typically 106 number of cycles [5]. As load cycles accumulate, initiation of crack is followed by propagation or enlargement of the crack in service. Several experiments have shown that the crack length is an exponential function of the number of cycles [6]. This means that crack growth is very slow until the final stage of fatigue life, where a relatively short number of cycles will result in fast crack growth leading to failure. The final stage of fatigue crack growth occurs when the crack-growth rate accelerates under the influence of ductile tearing or cleavage and the crack grows to such size that failure can occur at the next applied load cycle.[7][8]

2. LABORATORY EXAMINATION AND CORROBORATION

A 4-meter pipe was cut out and investigated in the laboratory. Chemical Analysis was carried out using a spark emission spectrometer for confirmation of the material and its comparison to API 5L specifications [9]. The results of the chemical analysis are detailed in table 2.

Table 2: Chemical Composition of failed pipeline

	C	Si	Mn	P	S	Cr	Ni	Al	Cu	Nb	Mo	V
API 5L-X65	0.12 max.	0.35 max.	0.8 - 1.5	0.015 max.	0.005 max.	0.3 max.	0.3 max.	0.02 min.	0.3 max.	0.05 max.	0.25 max.	0.08 max.
Failed Pipe	0.08	0.22	1.28	0.013	0.004	0.02	0.02	0.03	0.01	0.04	0.01	0.03

Mechanical Properties of the failed pipe was evaluated. A flat pinhole type of tensile test specimens of 132mm length with 50 mm gauge length of 6 x 6 mm2 square crosssection was fabricated along the pipe longitudinal direction. Similar samples of 85mm length with a 25mm gauge length & area of 6 x 4mm2 were fabricated across the weld. The tensile tests were carried out in a Universal Testing Machine. The results of the tests are shown in the Table-3. The UTS, YS and elongation values of the parent metal is found to be complying with the specification requirement of API 5L X65Also, from the results, it is seen that the weld properties are sound.

Table 3: Mechanical properties of failed pipe

UTS [MPa]	YS [MPa]	% Elongation	% Reduction in area
Parent Metal			
531	448	API 5L	
570	490	25.3	35.9
575	537	24	36.9
570	530	24	37.0
565	482	25	35.6
Weld			
582	505	20	24.2
580	505	25	23.9

Sub size samples of 5mm x 10mm x 55mm for Charpy impact tests were fabricated with sample lengths along the pipe longitudinal axis. The notch orientation was kept on the length – thickness plane. The tests were performed at temperatures at 25^0 C, 0^0 C and -20^0 C. The results of the tests are shown in Table-4. The results show that the material possesses good impact energy as well as the ductile-brittle transition temperature

Hardness measurements were carried out at the parent metal, heat affected zone and weld metal of the pipe away from the failure initiation zone. The results indicate a hardness value in the range of 93.2 to 95.9 HB.

Table 4: Charpy Impact test results

Temp. **(0C)**	Impact energy in joules
25	142, 138, 147
0	116, 77, 77
-20	78, 72, 76

Fractography of the pipe was carried out in the pipeline. Fine weld defects were observed from the inside of the pipeline. Based on the detailed laboratory study, it is concluded that rupture failure of the pipe has occurred by initiation of microcracks at the small weld defects and their propagation through fatigue caused by cyclic operating pressure (figure 5).

The positive interaction of closely spaced microcracks is inferred to have led to a large equivalent crack size eventually causing the rupture of the pipe.[10][11]

Figure 5a: Weld defects visible in HAZ& weld zone

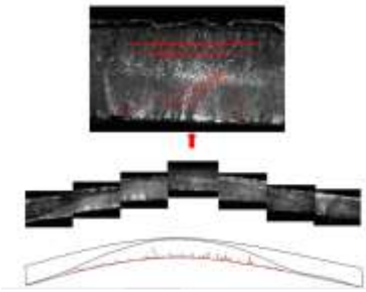

Figure 5b: Weld defects visible in HAZ& weld zone

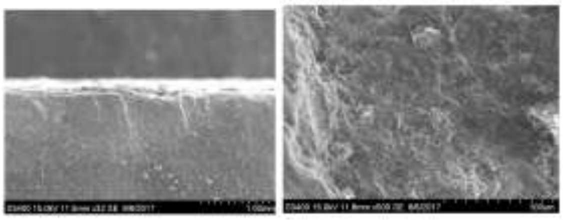

Figure 6: Fractography of fractured surface

Fractography showing the absence of dimple feature typical of brittle fracture. (Figure 6)

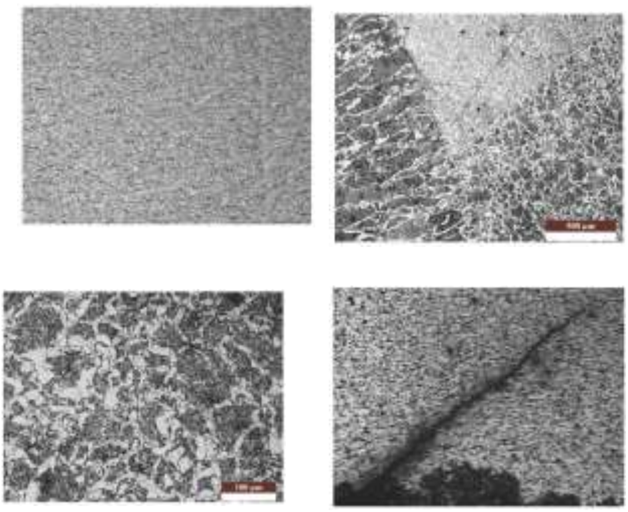

Figure 7: Microstructure of pipe near fracture – a) Parent Metal, b) Weld c) Heat Affected Zone d) Near failed area inclusion of type-B and type-D which is acceptable. [9]

3. RESULTS & DISCUSSION

- The pipe material conforms to API 5L X 65 grades with higher tensile properties than the minimum specified values.
- Multi-nucleation of cracks along the heat affected of the weldment at the fracture initiation zone observed. The propagation of the cracks is inferred to be by fatigue mode toward the outer surface. Since this zone contains large nos. of smaller through cracks, no significant plasticity is observed.
- The fracture surface at the point of failure reveals a flat profile throughout the pipe thickness. A Flat fracture surface with the absence of localized deformation, further confirms the crack propagation through fatigue on account of cyclic pressure. Presence of small weld defects enhances the probability of nucleation of microcracks.
- The sectional metallography at the end of the rupture reveals a fine-grained ferrite-pearlite with the presence of a crack from the pipe internal surface at the HAZ. Significant grain flow along the crack path is seen due to higher crack tip stresses.
- The initial fracture propagation by fatigue resulted from the growth of multiple cracks in the thickness direction, followed by positive interaction of these closely spaced microcracks leading to a large equivalent crack size. The large equivalent crack size eventually caused rupture of the pipe

4. CONCLUSION

Based on the detailed laboratory study, it is concluded that rupture failure of the pipe has occurred by initiation of microcracks at the small weld defects and their propagation through fatigue caused by cyclic operating pressure. The positive interaction of closely spaced microcracks is inferred to have led to a large equivalent crack size eventually causing the rupture of the pipe.

5. PRESENT RESEARCH AND WORK REQUIRED

The above pipeline failure is due to fatigue caused by cyclic loading puts a greater challenge for Pipeline operator as such unprovoked failures are not predictable due to limitations of existing technology. The strict environmental laws, potential fire hazards and groundwater contamination etc. are threats to pipeline operators. The cyclic loading due to pressure variations is a phenomenon in a pipeline which is not avoidable in totality for liquid pipelines. Hence research work is required for an in-line Inspection Technology tools both using Circumferential MFL or shear wave UT to precisely detect the microcracks particularly, in HAZ as a warning sign to the operator. Hence both detection accuracy & threshold limit and the probability of detection are expected and required to be improved with the passage of time for benefit of pipeline operators.

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