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Root cause analysis of Rupture in a Cross Country Crude Oil Transportation Pipeline - A case study

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ABSTRACT

An API 5LX65 grade cross country crude pipeline of 24" dia. ruptured along the longitudinal seam after a service life of 18 years. Multiple failures have occurred in this line since last few years. Detailed failure laboratory investigation has been carried out on the cut spool piece from the failed pipe to establish the root cause of failure.

From the investigations, the failure has been attributed to the nucleation of micro cracks from pre-existing lack of fusion defects at pipe longitudinal seam weld and their growth by fatigue arising from the pressure cycles experienced in liquid pipelines. The growth of these cracks up to 80% of pipe wall thickness and the simultaneous interaction of similar such adjacent fatigue cracks has led to the axial defect dimensions exceeding the critical dimensions needed for longitudinal rupture.

Keywords: micro cracks; Fatigue; Rupture; Fusion Defects; Pressure Cycle

INTRODUCTION

Underground Cross-country pipelines are used for safe, cost-effective, energy-efficient and environment-friendly mode for transportation of the Oil & Gas by Petrochemical Industries. The loss of mechanical integrity of such pipelines has occurred on numerous occasions worldwide. Literature reports from various databases on pipeline failures indicate a failure rate 2.8 - 3.4 per 10000km per year [1-4]. The failures of pipelines have been reported due to a variety of causes such as corrosion, external impact, defects, operational errors and natural hazards.

One such rupture failure occurred in cross country crude pipeline (API 5LX65 grade) of 24" dia. along the longitudinal seam after a service life of 18 years. Pipeline was constructed in 1996 and being used for transportation of crude oil from Gujarat coast to one of the inland refinery. This pipeline was originally designed for petroleum product service and was changed to crude oil service from 2006. Since 2014, multiple failures have been reported in this line after 8 years of service in crude transportation. The failure is of huge concern to the pipeline operators in view of environmental damage, public safety and production loss. It was desired to carry out failure investigation to establish the root cause of failure. The following enumerates findings of the study.

EXPERIMENTAL PROCEDURE

VISUAL INSPECTION

The as received photograph of the failed sample is given in Fig.1(a) and Fig.1(b). The failed pipe reveals a longitudinal rupture opening. The total length of the fracture is measured to be 1520 mm. The fracture is seen to have initiated along HAZ and propagating towards parent metal. A closure look at the rupture surface indicates a number of pockets of fatigue fracture zone extending to a different extent along the pipe thickness direction (Fig.1(c)). No signs of external surface corrosion marks are seen. The internal surface of the pipe is also seen to be free from any appreciable pitting or corrosion /metal loss in the fracture zone.

STERIOSCOPY

The fracture initiation zone as seen under stereoscopic microscope reveals multiple fatigue crack initiation in close proximity at the inner surface propagating towards the outer edge (Fig.2a). The whole rupture line segmented in 1 inch lengths over the 38 inch length of the spread on either side to the fracture initiation zone, revealed multiple nucleation of crack from the inner surface to a varied depth in thickness direction (Fig. 2b). Presence of a microscopic groove of 0.36mm depth is also observed at a distance of 0.2 mm from the inner surface all along the fracture length (Fig. 2(a) to (c)). The Individual cracks in the fracture initiation zone are seen to be initiated from this microscopic groove and growing to a maximum of 0.6mm along the thickness direction. Individual cracks are also seen to be joining at the midsection (Fig.2(d)). A graph showing the extent of fatigue region and fast fracture region across the thickness along the rupture line is shown in Fig. 2(e). A clear fatigue zone of 80% of the thickness at the initiation point is observed. The crack length along longitudinal axis of the pipe at fracture initiation zone is measured to be around 40 mm. Also, some amount of weld misalignment as well as weld defect (LOF) are observed on the failed sample (Fig. 3).

CHEMICAL COMPOSITION ANALYSIS

The chemical composition of the pipe has been analyzed using a spark emission spectrometer. The results are given in Table-1. The composition is seen to confirm to the API 5L requirement.

SECTIONAL METALLOGRAPHY & INCLUSION RATING

General microstructure of the pipe material has been studied along the pipe CT-section. Microstructure reveals a fine grained ferrite with distributed pearlite as shown in Fig.4(a) to Fig.4(d). The weld microstructure indicates a normal dendritic structure. The inclusion rating of the parent material indicated presence of thin inclusion of type-A and type-D.

SEM FRACTOGRAPHY

The fracture surface has further been evaluated under the Scanning Electron Microscope (SEM. The SEM Fractography confirmed the presence of microscopic defects at inner surface of the failed pipe (Fig.5). Also, the fatigue crack propagation zone near the crack initiation point along with the flat fracture surface could be seen.

TENSILE TESTING

Tensile tests on a flat pinhole type of test specimens of 50 mm gauge length and 6 mm x 6 mm square cross section along the pipe longitudinal directions and samples of 25mm gauge length across the welds have been fabricated and tested. The results of the tensile tests on failed pipe and virgin pipe sections carried out in a Universal Testing Machine are compiled and shown at Table-2(a) and Table-2(b) respectively. The UTS, YS and elongation values of the parent matel are found to be complying with the specification requirement of API 5L Gr.65. Examination of Fracture surface of the tensile specimen clearly indicates the presence of service induced fatigue crack zone at the inner edge with a depth of around 2mm (Fig.6). Yield strength and percentage elongation on the samples along weld transverse direction with full thickness of the pipe with weld reinforcement could not be measured due to the presence of service induced fatigue cracks.

CHARPY IMPACT TOUGHNESS EVALUATION

Charpy V-notch Impact sub size samples of 5mm x 10mm x 55mm were fabricated with sample lengths along pipe longitudinal axis with their notch orientation on the length – thickness plane. The tests have been performed at temperatures ranging within 25°C to -60°C to obtain the ductile to brittle transition temperature. The results are given at Table-3. The Impact energy values are seen to be of the same order as that of values reported in material test certificate.

BULK HARDNESS

Bulk hardness measurements have been conducted on the pipe surface using Rockwell hardness tester. The values varied within 97.3-97.6 HRB (222- 228BHN). These values are seen to be in conformance with the material test certificates.

NDT EVALUATION

Phased Array Ultrasonic Testing in order to assess the entire failed pipe for the presence of crack like defects, porosity etc. in the longitudinal weld seam. The PAUT studies indicated presence of three discontinuities of length 10 mm each and another of length 120 mm. The radiography of these locations containing the defects indicated the presence of intermittent lack of side wall fusion (Fig. 8).

RESULTS

* Pipe material conforms to API 5LX 65
* Effect of local residual stress is seen to be insignificant.
* Base metal possesses good fracture toughness value, tensile properties and impact properties.
* Tensile fracture surface of weld transverse sample reveals pre-existing fatigue crack zone.
* Unfailed regions adjacent to pipe rupture reveals presence of pre-existing defects characterized as Lack of fusion which are further confirmed by Phased array ultrasonic testing.
* Visual inspection, microscopic observation by stereo microscope and SEM further confirm the growth of the pre-existing defects by fatigue.
* Using API579 guidelines [4] and fatigue properties of the material, Fatigue crack growth time to almost 80% of the thickness was estimated
* Using in-house developed Fracture mechanics software based on BS7910 [5], the critical crack dimension for rupture through longitudinal crack is estimated as 40 mm for the maximum operating pressure of 73kg/cm2.
* The resultant dimension of the crack that led to the rupture has been measured on the failed piece and verified against the estimated critical dimension.
* Thus failure nucleation is thus attributed to formation of micro-cracks from pre-existing lack of fusion of the longitudinal weldments, their growth by fatigue in thickness direction to 80% of the pipe wall thickness.
* No of fatigue cracks and their simultaneous interaction in the pipe longitudinal direction is seen to have led to the axial defect dimension assuming values more that the critical dimension leading to the longitudinal rupture.

Table 1: Chemical composition of pipe material

	C	Si	Mn	P	S	Cr	Ni	Al	Cu	Nb	Mo	V
Failed Pipe	0.106	0.172	1.12	0.015	0.004	0.004	0.022	0.03	0.01	0.042	0.003	0.027
API 5L Gr.70	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.

Table 2(a): Tensile test results of failed pipe material

UTS, MPa	YS, MPa	% Elongation	YS / UTS	Reduction in Area (%) / Remark
Parent Metal (pipe longitudenal direction)				
611	559	22.9	0.91	66.12
611	545	28.1	0.89	65.54
587	536	24.1	0.91	66.12
595	531	24.9	0.89	62.40
581	520	23.9	0.89	61.11
617	557	18.4	0.90	66.63
Weld (Circumferential direction)				
562				Samples were with full thickness of the pipe with weld reinforcement. Fracture started in the HAZ/Fatigue zone
596				
493				
596				
474				
589				
560	503	18.0		Samples were machined for uniform thickness in the gage section.
564	505	19.0		

Table 2(b): Tensile test results of virgin pipe material

UTS, MPa	YS, MPa	% Elongation	YS / UTS
Parent Metal			
640	590	24	0.92
526	460	24	0.87
534	475	22	0.89
Weld			
456	400	28	
549	500	28	
546	496	28	

Table 3: Tensile test results of failed pipe material

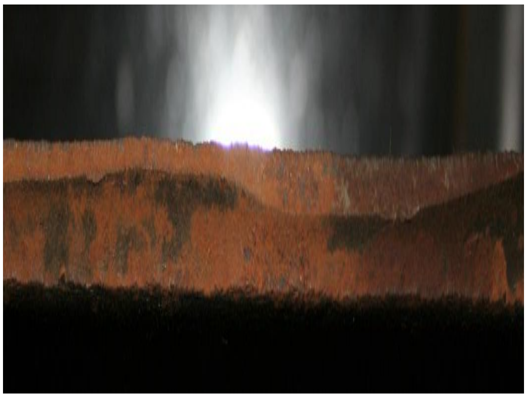
Temp. (0C)	Impact Energy (Joules)
25	96.9,79.9,82.6
0	91.4,78.9,80.3
-20	77.9,71.7,76.1
-40	65.7,66.5,61.3
-60	66.5,67,65.1

Fig. 1(a): View of failed pipe

Fig. 1(b): Fracture initiation region

270 mm from the fracture initiation region (on the left side) showing 5% of fatigue zone in the thickness direction.

575 mm from the fracture initiation region (on the left side) showing 60% of fatigue zone in the thickness direction



675 mm from the fracture initiation region (on the left side) showing 50% of fatigue zone in the thickness direction.

900 mm from the fracture initiation region (on the left side) showing 60% of fatigue zone in the thickness direction

Fig. 1(c): Other pockets of fatigue crack initiation points

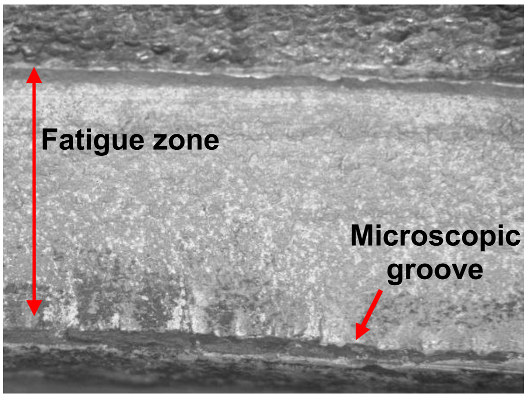


Fig 2a: Fracture initiation region revealing multiple fatigue crack initiation

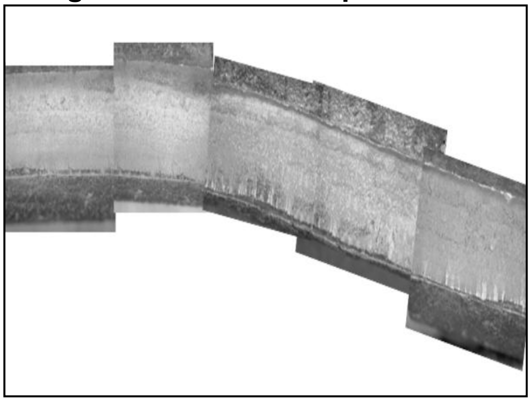


Fig 2b: Multiple crack initiation at different pockets along fracture line at two different magnifications

Fig 2c: Showing joining of micro cracks in mid section

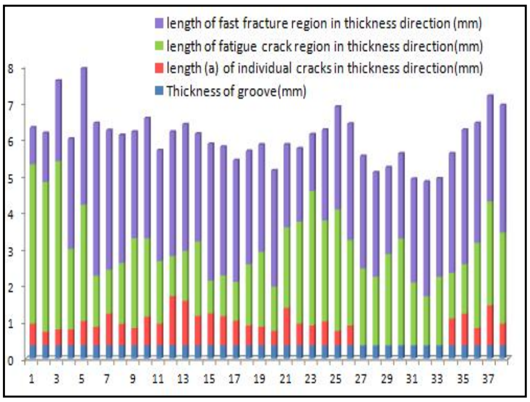


Fig 2d: Extent of fatigue and fast fracture region across the thickness along the rupture line

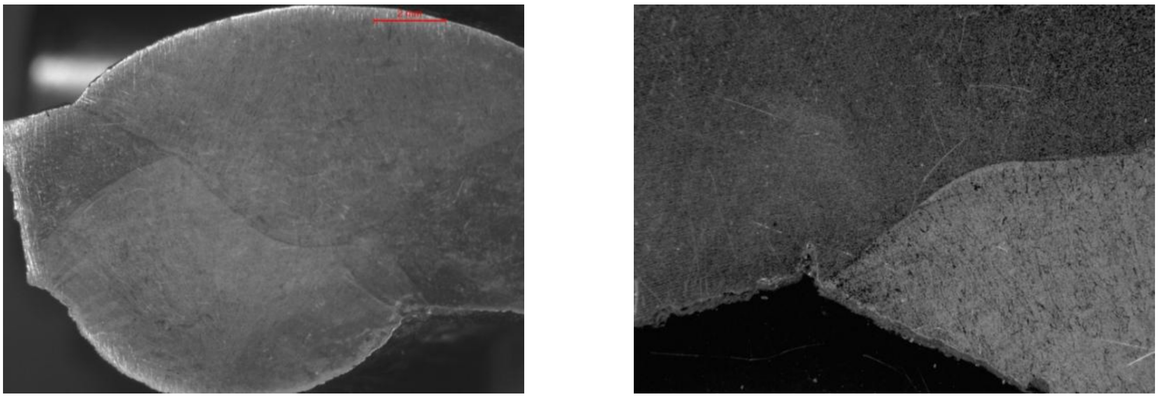


Fig 3: Weld region showing weld misalignment as well as weld defect (LOF)

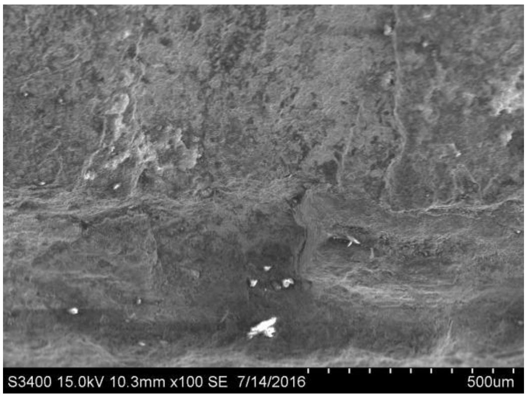


Fig 5: SEM Fractograph

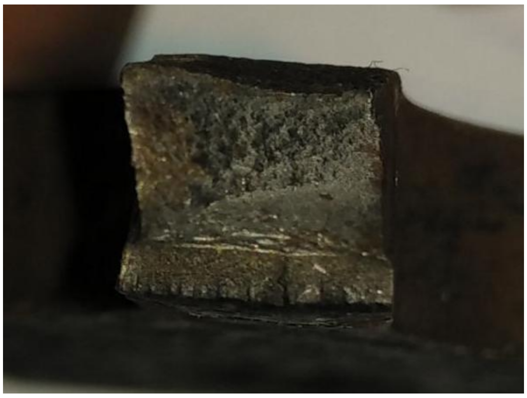


Fig 6. Fracture surface of broken tensile specimen.

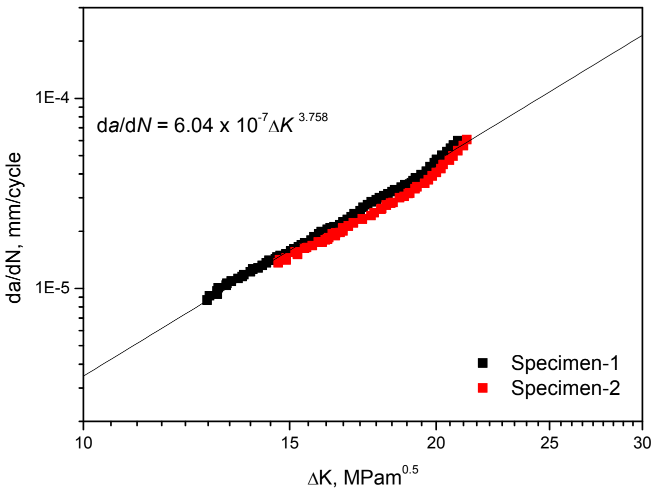


Fig. 7: The test curves for da/dN

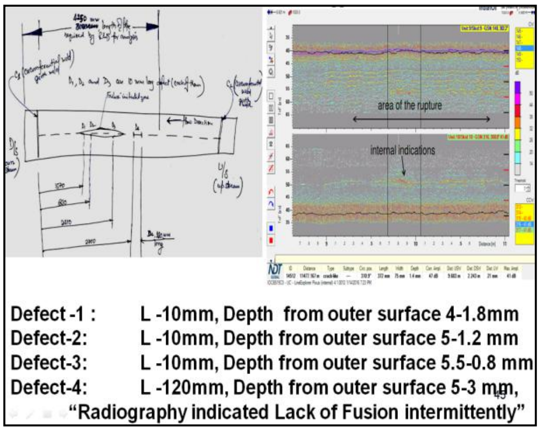


Fig. 8: NDT Findings on ruture line

CONCLUSIONS

Root cause of failure is attributed to nucleation of number of micro cracks from the pre-existing Lack of Fusion at pipe longitudinal seam weld and their growth by fatigue in the thickness direction. No of such fatigue cracks and their simultaneous interaction in the pipe longitudinal direction is seen to have led to the axial defect dimension assuming values more that the critical dimension leading to the longitudinal rupture.

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