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Fatigue Failure of Outlet Pipe Work of Flare System at Natural Gas Processing Plant

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Abstract

The natural gas produced from subsea wells is processed through different stages before being supplied through pipelines for local market or export. Processing of the produced natural gas is started with separation of gas and liquid using a slug catcher that is connected to a flare system. The flare system consists of piping made of 16" diameter branches connected to 20" diameter header using circumferential weld with a total of seven joints. The pipe work of the flare system is made of 316L stainless steel and it is operated in an interrupted mode. Design and operation pressures are 142 bar g and 88 bar g while design and operation temperatures are -40^{o}C and 20^{o}C, respectively. After five years of normal service, one of the seven joints of 16" branch/20" header has experienced failure. Based on different non-destructive and destructive tests, it is concluded that this premature failure is attributed mainly to fatigue damage. It is believed that acute or sharp angle of 16" branch/20" header connection that acts as a local stress raiser played a remarkable role in initiation of fatigue damage on outer surface, just beside circumferential weld. In addition, low stress high frequency vibration of the subject pipe work, due to mainly several emergency shut down operations, has accelerated initiation of fatigue damage. In order to minimize the possibility of such failure in future, design of 16" branch to 20" header connection was modified where a compensation plate fitted was used to minimize stress concentration at this connection zone.

Keywords: Natural gas processing, Flare system, 316L stainless steel, Stress concentration, Vibration, Fatigue

1. Background

A natural gas production plant has been set into operation about twelve years ago. The natural gas produced from subsea wells is processed through different stages before being supplied through pipelines for local market or export. Processing of produced natural gas is started with separation of gas and liquid using a slug catcher that is connected to flare system to be used in case of emergency plant shutdown. The flare system consists of piping is made of 16inch diameter pipes connected to 20inch diameter header using circumferential weld with a total of seven joints. Nominal thickness of 16" pipes is 4mm while that of 20" header is 6mm. The pipe work of the flare system is made of 316L stainless steel and it is operated in an interrupted or irregular mode. Design and operation pressures are 142 bar g and 88 bar g, respectively. Design and operation temperatures are -40^{o}C and 20^{o}C, respectively.

After five years of normal service, one of the seven joints of 16" pipe/20" header has experienced failure where fracture has occurred at its conjunction zone. A spool including fracture zone was subjected to different non-destructive and destructive investigations for failure analysis.

2. Investigations

The failed spool was subjected to different non-destructive and destructive tests including visual investigation, liquid penetrant test, radiographic test, chemical analysis, thickness measurement, macro-, optical and scanning electron microscopic examinations, hardness measurements, tensile and impact tests. General and enlarged views of the fracture zone of the spool are shown in Fig. 1. The important notice is that fracture had occurred at the acute or sharp angle zone of 16" pipe/20" header assembly, just beside its circumferential weld. Based on visual investigation, it can be deduced that fracture was started at its mid-length then, propagated in tow opposite directions along circumference. The fracture extended less than half way around the circumference of 16" pipe/20" header. Visual and dye penetrant inspections indicated surface cracks on both sides of the fracture termination zones (Fig. 1-b). Generally, the outer surface of the failed spool is clean and free from deposits or indications for corrosion. Visual investigation of the weld face and root sides of the circumferential weld of 16" pipe/20" header as well as that of 16" pipe showed less weld quality. However, dye penetrant test of both root and face sides of circumferential weld of 16" pipe showed no surface cracking.

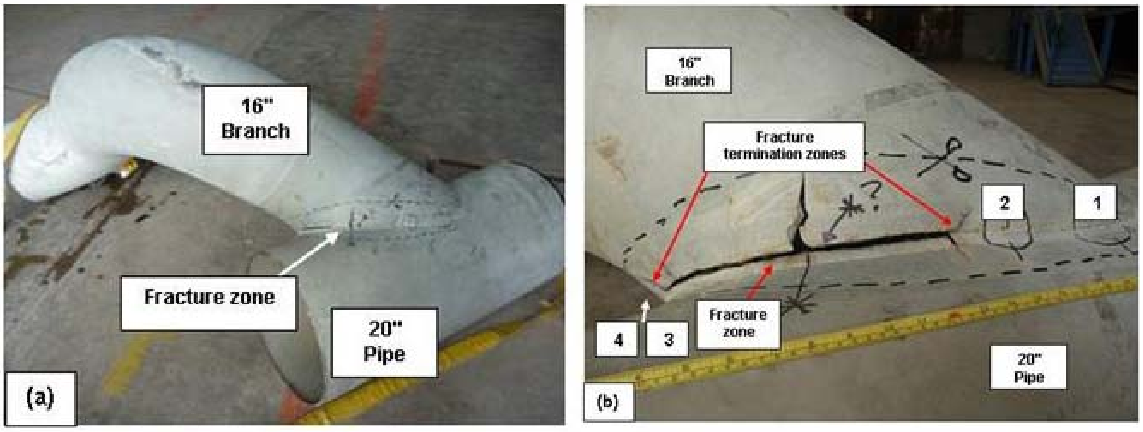

Figure 1. General (a) and enlarged (b) views of fracture zone of the spool. Note that fracture had occurred at sharp angle zone of 16" pipe/20" header assembly, just beside its circumferential weld.

Visual investigation of the internal surface of the failed spool showed damage at the inner surface of 16" pipe, which could be related to mechanical action. Except that, the internal surface of the spool showed smooth surface with no indications for internal corrosion. In other words, no thinning or variation in the wall thickness was observed, where almost uniform wall thickness (~6.0mm for 20" pipe and ~4mm for 16" branch) was obtained at both fractured and non-fractured zones. Macro- and microscopic investigations of a cross section taken from mechanically damaged zone showed internal localized reduction of about 0.6mm depth in the wall thickness of mechanically damaged zone. Optical microscopic investigation showed no indication for cracking at mechanically damaged zone.

Surface cracks zones observed around the fracture termination zones (zones 1, 2, 3 & 4, in Fig. 1-b) were subjected to detailed investigation. Close-up views of zones 4 and 1 at front of the fracture termination zones are shown in Fig. 2-(a) and (b). It can be noticed that surface cracks are existed just beside circumferential weld of 16" pipe/20" header. Visual and dye penetrant examinations of zones 3 and 4 showed similar results.

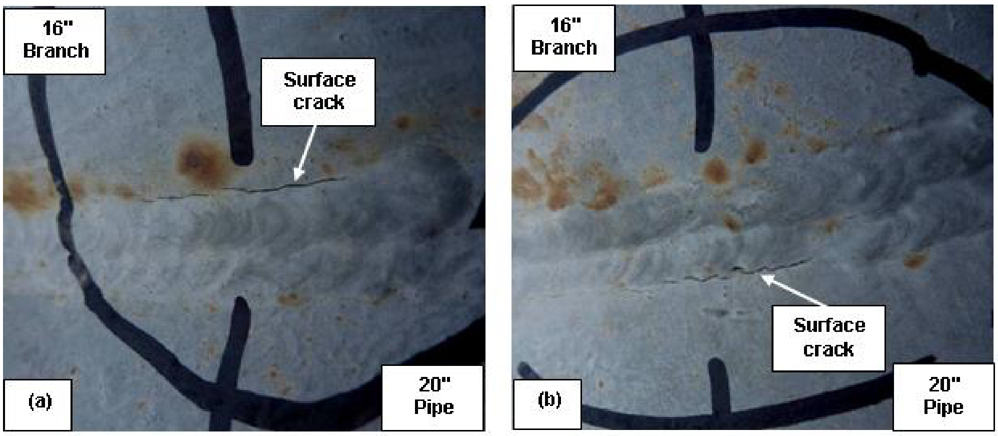

Figure 2. Close-up views of zones 4 and 1 at front of fracture termination zones of Fig. 1-b. Note surface cracks on both sides of circumferential weld of 16" pipe/20" header.

After detailed visual and dye penetrant investigations, specimens from both fractured and non-fractured zones of the spool were cut out and prepared for chemical analysis, macro- and microscopic examinations, scanning electron microscopic examination, hardness measurements, tensile and impact tests. Results of chemical analysis of the failed spool together with the specified chemical composition range for type 316L stainless steel are shown in Table 1. It is obvious that the chemical composition of the used spool is a typical for the austenitic stainless steel type 316L.

Table 1. Results of chemical analysis (wt%) of the failed spool together with the specified chemical composition range for ASME-SA213, 316L stainless steel.

Material	C	Si	Mn	S	P	Cr	Ni	Mo
Failed spool (BM)	0.017	0.41	1.45	0.018	0.031	17.73	11.26	2.16
Failed spool (WM)	0.017	0.37	1.23	0.006	0.029	16.91	10.18	2.01
316L St. St.	<= 0.03	<= 1.0	<= 2.0	<= 0.03	<= 0.04	16.0~ 19.0	9.0~ 12.0	2.0 ~ 3.0

Cracked zones 1, 2, 3 and 4 in Fig. 1-(b) were cross sectioned where its cracking features were clarified. Macrographs of a cross section taken from cracked zone 2 are shown in Fig. 3. It is clear that the observed cracks are weld toe cracking type. Similar results were obtained for samples taken from zones 1, 3 and 4 in Fig. 1-b. Weld toe cracks of zones 2 and 3 (~18cm away from fracture termination zones) were propagated through thickness of 16" pipe. Weld toe cracks of zones 1 and 4 in Fig. 1-b (~35cm away from fracture termination zones) were propagated through thickness of 20" header. It is obvious that cracks were initiated at weld toe on outer surface then, propagated through thickness. Optical micrographs with high magnification of cross sections taken from zones 1 and 4 in Fig. 1-b are shown in Fig. 4. It can be noticed that normal austenitic microstructures for both base metal, HAZ and weld metal were obtained and cracks were propagated through grain boundaries. Survey of the hardness measurements indicated reasonable hardness values for the base metal, HAZ and weld metal, where average hardness values of 181HV, 183HV and 179HV were obtained for base metal, HAZ and weld metal respectively (Table 2). The given hardness values are the average of five readings. Results of the tensile test for both base metal and welded joint of the failed spool are shown in Table 3. The given tensile values are the average of three specimens. Results of the impact test, at different temperatures, of the base and weld metals of the failed spool are shown in Table 4. The given impact values are the average of three specimens. Results of both tensile and impact tests showed normal values based on specified properties for the used material.

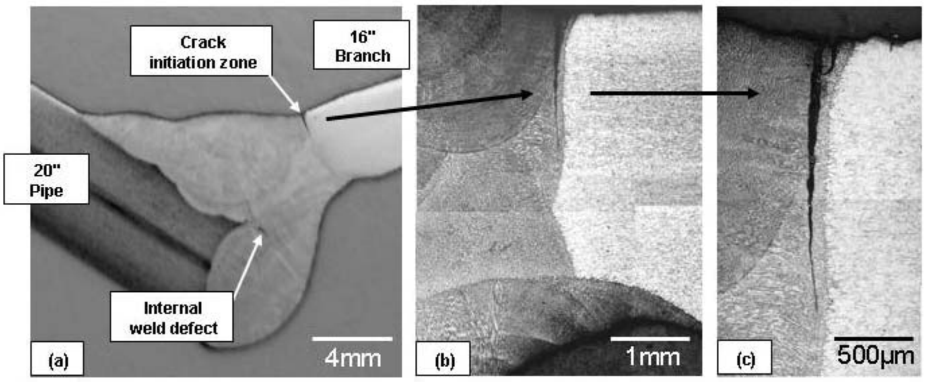

Figure 3 Macrographs of a cross section taken from zone 2 in Figure 1-b showing toe cracks propagated through thickness of 16" pipe.

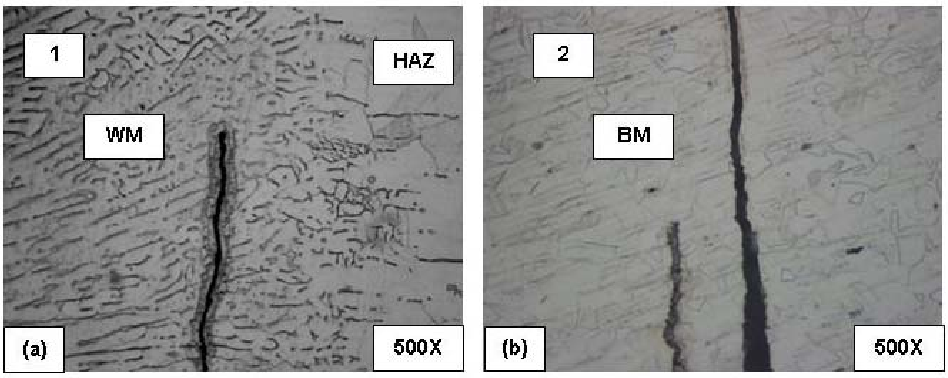

Figure 4 Optical micrographs with high magnification of cross sections taken from zones 1 and 4 in Figure 1-b. Note normal austenitic microstructures for base metal, HAZ and weld metal. Cracks were propagated through grain boundaries.

Table 2. Results of hardness measurements (HV) of fractured spool together with the specified value for ASME-SA213, 316L stainless steel.

Zone / Hardness	Base Metal	HAZ	Weld Metal	ASME-SA 213, 316L St. St.
HV	182	185	180	217 max.

The given hardness values are the average of five readings.

Table 3. Results of tensile test of circumferential welded joints together with the specified values for ASME-SA213, 316L stainless steel.

	0.2% Proof Strength (MPa)	Tensile Strength (MPa)	Elongation (%)
Base Metal	359	597	52
Welded Joint	---	593	---
ASME-SA 213, 316L St. St.	170 min.	485 min.	40 min.

The given values are the average of three tested samples.

Table 4. Results of impact test of circumferential welded joint together with the specified values for ASME-SA213, 316L stainless steel.

	Absorbed Energy, J		
	-5 °C	-10 °C	-15 °C
Base Metal	107	101	98
Weld Metal	107	97	95
ASME-SA 213, 316L St. St.	88-134 J (65-100 Ft.Ib) at 23°C		

The given values are the average of three tested samples.

In order to help in identification of failure mechanism, fracture surface was carefully examined using stereoscope and scanning electron microscope. Low magnification photographs of fracture surface of 16" pipe side of the spool are shown in Fig. 5. Crack initiation zones and fracture propagation directions are highlighted with arrows. It is obvious that multi-cracks were initiated at the outer surface, where smooth fracture surface can be seen, then propagated toward inner surface. In other words, crack suspected initiation zones at the outer surface appeared relatively smooth and associated with beach marks and a propagating ductile crack. Crack termination zones at the inner surface had a rough texture associated with the final fracture.

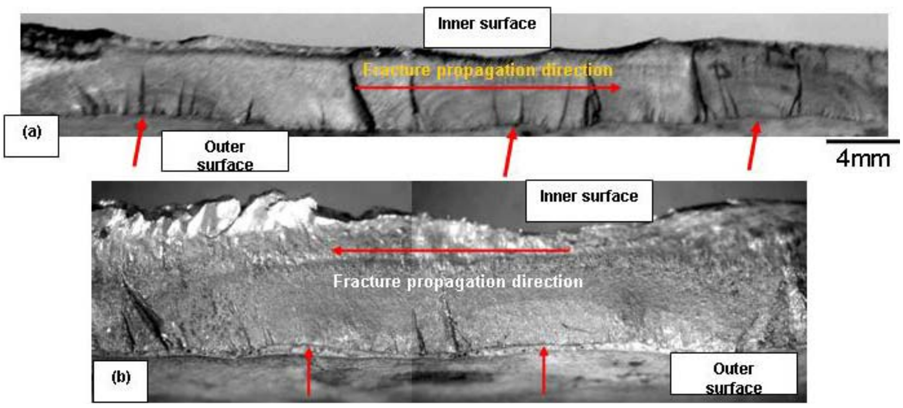

Figure 5. Low magnification photographs of fracture surface of <u>16" pipe side</u> of spool. Crack initiation zones and fracture propagation directions are highlighted with arrows. Note beach marks at crack suspected initiation zones.

Scanning electron microscopic photographs with different magnifications of fracture surface including suspected initiation zones are shown in Fig. 6. Crack initiation sites can be seen on the outer surface, where a single macroscopic direction of crack propagation is impossible to be defined. This is because crack size is still in the microcrack zone, where multiple cracks form at the surface, initiating at different locations and with different orientations. The important notice is the unclear fatigue striations at the fracture initiation zones.

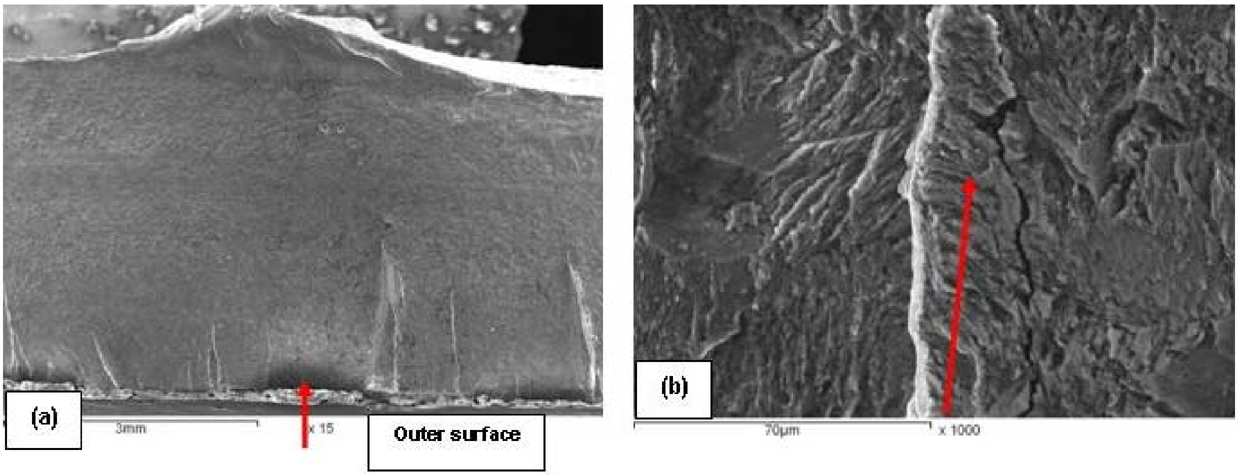

Figure 6. Scanning electron microscopic photographs of fracture suspected initiation zones at outer surface showing unclear fatigue striations.

3. Discussion

Visual and dye penetrant examinations of the failed spool showed that the fracture zone was confined to the acute or sharp angle of 16" pipe/20" header assembly, just beside circumferential weld line. Such sharp angle is considered as stress concentration zone. The fracture was initiated at the outer surface and propagated through thickness in two opposite directions where it was extended less than half way around the circumference. No indications for corrosion attack were observed on spool outer or inner surface. Only, mechanically damaged zone was observed at the inner surface of 16" pipe and this could be occurred long time ago during construction or repair works. However, such mechanical damage played no role in the current failure. In general, non-destructive investigations showed less weld quality. Meanwhile, fracture was not directly related to welding defects since fracture had occurred in the base metal just beside weld line.

Based on the results of chemical analysis, hardness measurements, tensile and impact tests and microscopic examination of the failed spool, materials of both base and weld metals were found to be within the specification of type 316L austenitic stainless steel. Macro- and microscopic examinations of cross sections around the fracture zone showed multi-cracks initiated at the weld toe that is considered as another stress concentration zone. Stereoscopic examination of the fracture surface showed that multi-cracks were initiated at the outer surface where smooth surface with beach marks was observed. Scanning electron microscopic investigation of the fracture surface showed unclear fatigue striations at the fracture suspected initiation zones. These findings support fatigue damage as a failure mechanism [1-5].

Fatigue failure is the phenomenon leading to fracture under repeated or fluctuating stresses that are less than the tensile strength of the material. Fatigue fractures are progressive, beginning as minute cracks that grow under the action of fluctuating stress. There are three stages of fatigue failure: initiation, propagation, and final fracture. The location of the initiation is at a stress concentration [6-9]. It is believed that stress concentration in the subject case is attributed mainly to the acute or sharp angle zone of 16" pipe/20" header assembly. In other words, such acute or sharp angle worked as site for initiation of fatigue damage at weld toe on outer surface of 16" pipe/20" header assembly, just beside its circumferential weld line.

The current piping system is subjected to more than just static forces. They can have severe vibrations induced mainly due to several start up operations. Vibration can be also induced due to temperature change. Since the piping system is operated in an interrupted or irregular mode, it is subjected to low stress high cycles fatigue. Under such repeated conditions, fatigue crack could be initiated at the highest stress concentration zone (acute angle zone). After the original fatigue crack is formed, it becomes an extremely sharp stress concentration that tends to drive the crack ever deeper into the metal with each repeating of the stress. The local stress at the tip of the crack is extremely high because of the sharp “notch,” and with each crack opening, the depth of the crack advances by one “striation”. Fatigue striation is not clear at the fracture initiation zone due to low stress cycles. As the propagation of the fatigue crack continues, gradually reducing the cross-sectional area, it eventually weakens the material so greatly that final, complete fracture occurs.

Conclusions and Recommendations

Based on the results obtained in this investigation, it can be concluded that the subject premature failure is attributed mainly to fatigue damage. High stress concentration at the acute or sharp angle of 16" pipe/20" header assembly and low stress high frequency vibration due to mainly several start up-shut down operations, both have shortens the lifetime of the spool. Fatigue failure is the phenomenon leading to fracture under repeated or fluctuating stresses that are less than the tensile strength of the material. The initiation site of fatigue failure is minute, never extending for more than two to five grains around the origin. The location of the initiation is at a stress concentration. It is believed that the acute or sharp angle of 16" pipe/20" header assembly that acts as local stress raiser played a remarkable role in initiation of the fatigue damage on the outer surface, just beside circumferential weld. It is obvious that the fracture initiated at the outer surface and propagated across the thickness in two opposite directions. As the propagation of the fatigue crack continues, gradually reducing the cross-sectional area, it eventually weakens the material so greatly that final, complete fracture occurs.

As a preventive measure, the other six connections of 16" pipe/20" header were subjected to visual and dye penetrant tests where absence of external surface cracks was confirmed. In order to minimize the possibility of such failure in future, the design of 16" pipe to 20" header connection was modified, where a compensation plate fitted was used to minimize stress concentration at this connection zone. Besides, circumferential welds were made with a better quality even it had no direct relation with the failure.

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