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Role of Welding Defects on the Failure of Sub-sea Carbon Steel Gas Pipeline

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***Abstract*— Sub-sea gas pipeline spool made of a carbon steel alloy API 5XL grade X52 was failed at a girth weld adjacent to 45^0 elbow after 5 years of operation. The nominal diameter of the failed spool is 4″. The failed spool was received for failure analysis and data collections. Examination of the interior surface of the spool revealed moderate general corrosion with few shallow pits except the area near the girth of the circumferential welds showed severe localized pits where the corrosion attack occurred at the fusion line between weld metal and heat affected zone. Based on the macroscopic, SEM and XRD analyses, the failure was occurred due to flow enhanced accelerated localized corrosion attack related to improper welding techniques of girth welds. Undercut and / or excess bead penetration at the weld root and high heat input could be the primary causes for the localized turbulent flow conditions created around the girth welds which in turn led to this accelerated corrosion failure assisted by thermally stressed heated affect zone of the base metal. The presence of corrosive elements such as Cl &S simultaneously with localized turbulent flow results in a rate of localized corrosion orders of magnitude greater than those caused by pure erosion or corrosion mechanism. A proper welding techniques carried out by qualified welders are recommended for prevention of similar failure in the future.**

***Index Terms*—Sub-sea gas pipeline spool, carbon steel alloy, corrosion-erosion attack, welding techniques, heat affected zone.**

I. Introduction

Carbon steel pipelines are extensively used in the petroleum industry for transmitting gas and oil from subsea wells to 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 [1]. The pipeline consists of high numbers of spools assembled by welding techniques. Every spool itself consists of many circumferential welding joints. Continues safe operation and failures prevention of these pipelines are therefore of vital national interest. The extent of internal corrosion in crude oil or gas carrying pipelines is generally influenced by many factors such as pipeline weld quality, temperature, CO_2, H_2S, O_2 content, chlorides, flow velocity, and surface condition of the steel [2-5]. This article analyses the failure causes of sub-sea welded spool received from Egyptian Petroleum Company failed during normal service after 5years from erection date and early before ending the twenty years of estimated remaining life assessment. The spool has 8 circumferential welds and leak occurred at a 4$''$ nominal diameter girth weld (no. 3) adjacent to a 45 degree elbow as shown in Fig. 1. The Spool including fracture zone was subjected to detailed failure analysis.

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II. Experimental Procedure

The spool was visually examined and then subjected to different non-destructive and destructive tests such as liquid penetrant test, chemical analysis, thickness measurement, macro-, optical and scanning electron microscopic examinations, hardness measurements and tensile tests. For metallographic observations, specimens near failed regions with a cross-section normal to the welding direction were cut from each joint and mechanically ground using emery papers down to 2000 grade, followed by polishing using 0.1μm agglomerated alpha alumina suspension solution, then rinsed and degreased with acetone. The macro- and microstructures of various weld regions were observed using optical microscope (OM). An X-ray diffract meter (XRD) with Cu Kα radiation and scanning electron microscopic mounted with EDS analysis (SEM-EDS) were used to examine the internal surface of the failed spool. Hardness measurement was carried out along the cross section transverse to the welding direction with an internal spacing of 0.5 mm under a load of 9.8 N for 15 s loading time. Tensile test specimens of the spool base metal were machined in the longitudinal directions and tests were carried out at room temperature at a strain rate of 1 mm/min.

III. RESULTS

Chemical analysis of the base metal and weld metals is shown in Table 1. The results showed the conformity of the tube material to the required specifications; API 5XL grade X52. The visual inspections after removing the external coat showed neither corrosion products nor mechanical damage along the received part. General and close-up views from the circumferential weld no. 3 of the fractured spool are shown in Figure 2. It can be noticed that fracture had occurred along the fusion line of the weld. Close-up views of the inner surfaces at the circumferential welds are shown in Fig. 3. The inner surface of the pipe showed moderate general corrosion and few shallow pits compared to the weld zone, which was seriously damaged. The circumferential welds numbered 1, 2, 4 and 5 have shown relative damage with deep grooves and rounded holes. The worst degradation of damage is observed at circumferential weld no. 1 while the least ones was no. 2. Girth Welds no. 6 &7 around the reducer and the flange weld no.8 showed grooves at fusion lines and excess penetration at the weld root beads.

Macrostructures of the cross sections normal to the welding direction are shown in Fig. 4. Severe and deep attacks along fusion lines between weld metals and heat affected zones rather than base metal are clearly observed in circumferential welds no. 2, 3, 4 and 5. Optical microstructures of base metal and weld metal of joint no. 3, revealed by Nital etchant solution are shown in Fig. 5. The microstructure of base metal (BM) is elongated ferrite - pearlite structure (Fig. 5a) which is typical for API 5L grade 52. The microstructure for weld metal (WM) consists of acicular ferrite, side plate ferrite and grain boundary ferrite (Fig. 5b). The structure of the heat affected zone (HAZ) consists of pearlite and upper bainite as shown in Fig. 5c. The HAZ grains are coarse near the fusion line and become finer as go far from fusion line (Fig. 5d). Detailed examination of the weld zone of weld no.3 showed defects (porosity) at both root bead and final bead of the weldment. The corroded area of the fusion line showed some remaining corrosion products as shown in Fig. 6. The tip of the remaining part of weld no. 3 after corrosion showed fine grooves and gullies.

Table 1 Chemical composition of weld metal and pipeline material.

Type	Chemical composition, mass %					
	C	Si	Mn	P	S	Fe
Weld metal	0.06	0.70	1.20	0.007	0.006	Bal.
Pipeline material	0.07	0.28	1.47	0.005	0.006	Bal.

Table 2 Results of tensile test of base metal.

	Yield strength N / mm2	Tensile strength N / mm2	Elongation, %
Grade API-X52	358 min.	455 min.	25 min.
Received spool	394	473	43

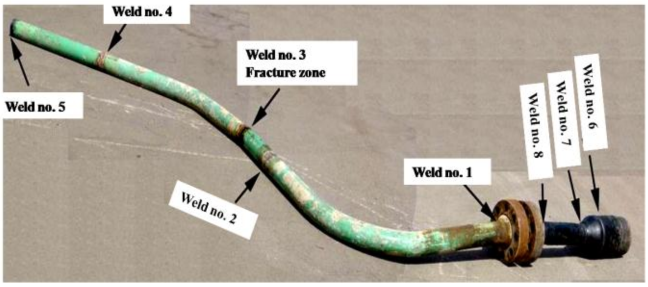

Fig. 1 Photograph of the received spool.

Same Corrosion damage phenomena was also observed at other weld joints as shown in Figs. 7&8, where the corrosion attack also started at HAZ near at the weld, exactly at fusion line. Examination of fracture surface of weld no. 3 at high magnification using SEM showed ductile dimpled fracture (Fig. 9a). Corrosion attack is characterized by deep groove, rounded holes and valleys (Fig. 9 b & c). Energy Dispersive spectroscopy (EDS) was also used to examine the fracture surface. An example of the EDS analysis of the weld no. 3 is shown in Fig.10. The aggressive elements such as Cl and S are quite present at mild concentrations. The XRD analysis of the corrosion products taken from the corroded surface and weld root is shown in Fig. 11. The results showed the presence of $Fe_3 O_4$, ($FeSO_3$. 2.5 H_2 O), Fe OO H, Fe S and Fe Cl. Macro Vickers hardness profile was carried out for base metal, HAZ and weld metal for weld no.3 as shown in Fig. 12. The hardness values of WM and HAZ were the highest (250Hv), while those measured for BM were the lowest (160 Hv). The hardness of HAZ is relatively higher than values specified by API 5Xl standard (~ 180 HV). The results of tensile test of the base metal are given in Table 2. These results are in a good agreement with the requirements of API 5XL standard for grade X 52.

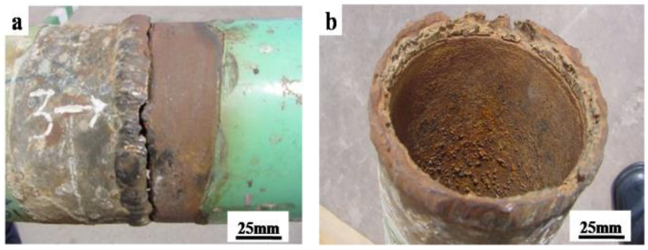

Fig. 2 Close–up view of the failed region adjacent to weld no. 3.

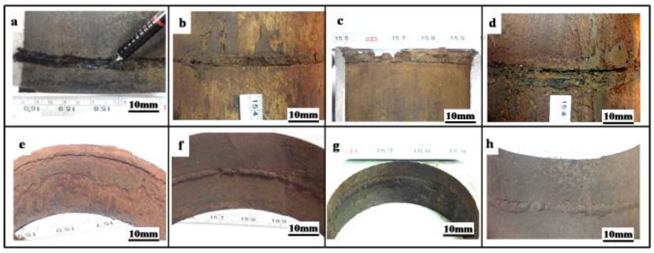

Fig. 3 Close-up views of inner surfaces containing welding zones : (a) weld no1, (b) no. 2, (c) no.3, (d) no. 4, (e) no. 5, (f) no.6, (g) no.7 and (h) no. 8.

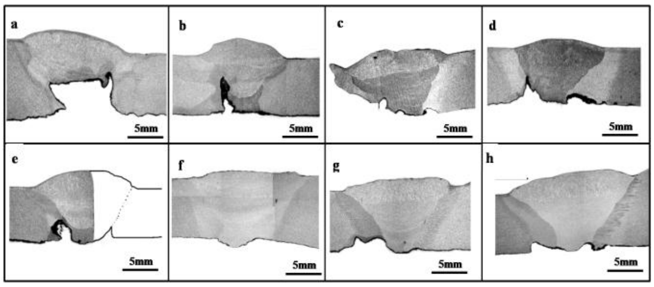

Fig. 4 Macrostructures at cross-sections of all girth welds : (a) weld no1, (b) no. 2, (c) no.3, (d) no. 4, (e) no. 5, (f) no.6, (g) no.7 and (h) no. 8.

IV. DISCUSIONS

Corrosion in gas pipe lines can be classified into three main categories, based on the type and nature of the resulting damage. General corrosion, the least dangerous form of attack in which metal is uniformly oxidized all over the surface.

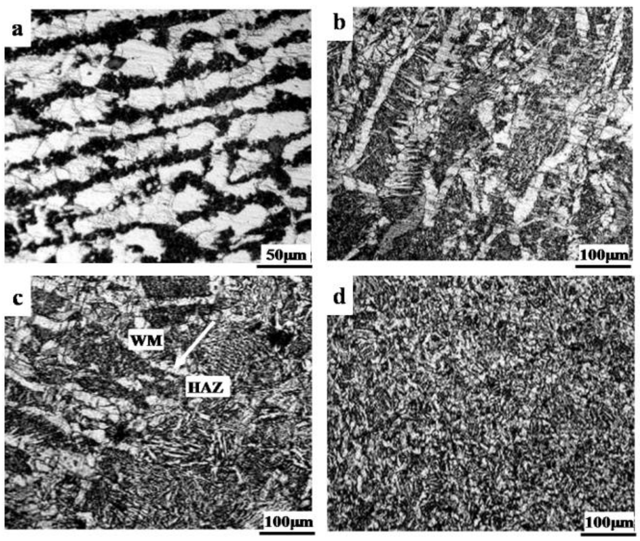

Fig. 5 Microstructures of the weld no. 3: (a) base metal, (b) weld metal, (c) fusion line and (d) fine heat affected zone.

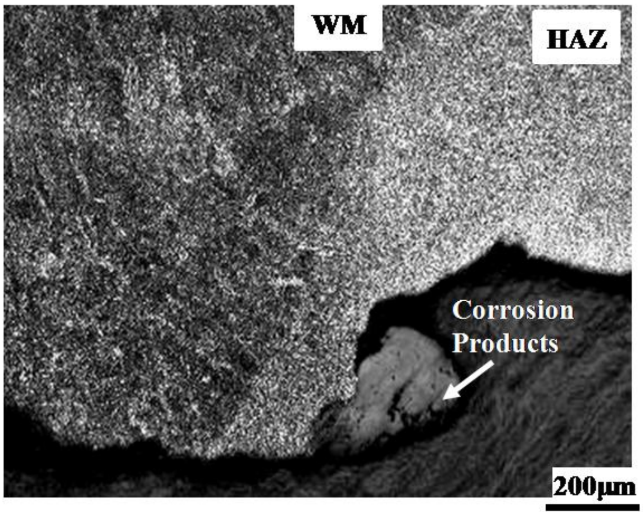

Fig. 6 Microstructures at the root of the weld no. 3 showing corrosion products.

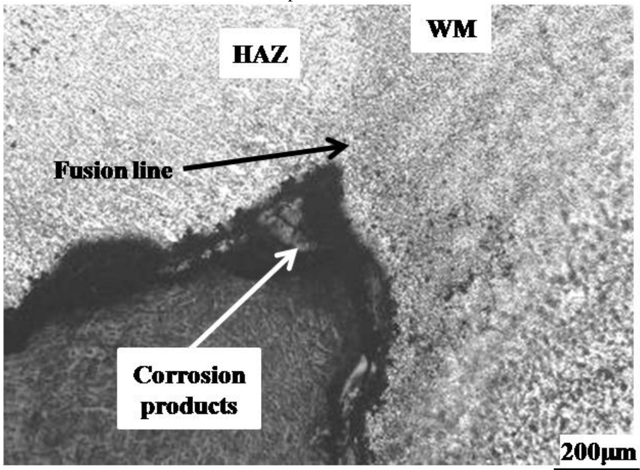

Fig. 7 Macrostructures at the root of the weld no.1 showing corrosion at fusion line.

The second one is localized corrosion. It is a selective removal of metals from the exposed metal surface.This covers pitting corrosion, crevice corrosion, galvanic corrosion and intergranular corrosion. The third type of corrosion is mechanically assisted localized corrosion in which the stresses induced within the metal itself lead to stress corrosion cracking without significant loss of material. Another form of mechanical stresses are those due to the movement of fluids such as erosion corrosion, impingement and cavitations corrosion [6-8]. These types of corrosion damages are affected by the velocity and nature of the flows. The examination carried out in this investigation showed that the pipe material is in conformity to the specs API 5XL grade X52. The fluid properties and operating conditions are relatively mild since the corrosion along the pipe line is almost insignificant excepting the regions around welding joints. The aggressive corrosion attack was localized around girth welds to different extents. Visual and macrostructures examinations of the weld cross-sections showed welding imperfections such as undercuts and excess penetrations. In addition, the corrosion attack has continued along the fusion line between WM and HAZ. When corrosion attacked two thirds of the pipe wall thickness as in the case of weld no.3, the operating pressure became greater than the remaining strength of pipe which in turn leading to failure as shown in Figs. 2-4.

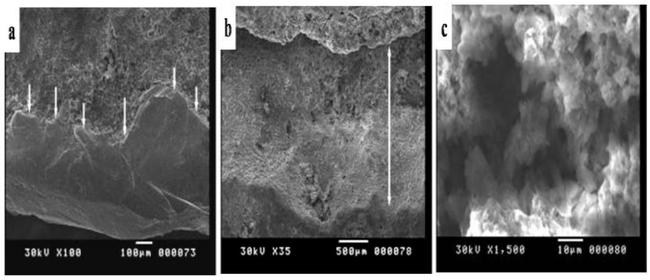

Fig. 8 SEM photographs: (a) fracture surface of the failed weld, (b) corrosion appearance at fusion line of the weld no. 3 and (c) the corroded surface at higher magnification.

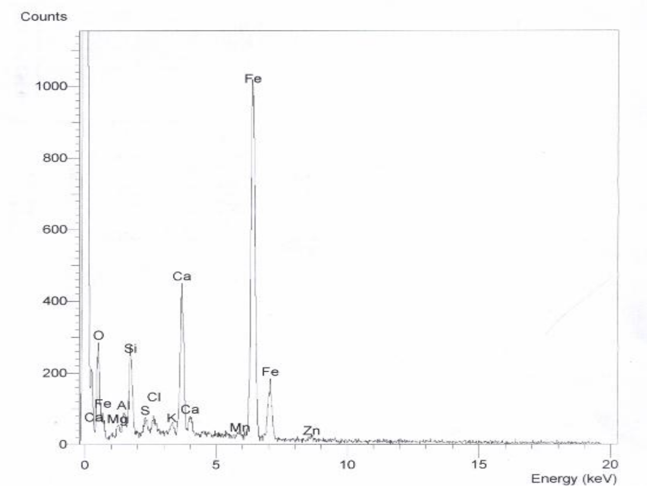

Fig. 9 Result of EDS analysis.

Since the investigation of interior surface revealed moderate general corrosion with few shallow pits, the ductile nature of the fractured surface revealed by SEM (Fig. 9 a, b) and corrosion morphology (Fig.10c) of the girth welds indicate that the spool was fractured due to erosion – corrosion mechanism. Erosion – corrosion is the acceleration of metal deterioration due to the relative movement between the fluid and metal surface [9-12]. Velocity strongly influences erosion-corrosion, yet it is not the origin for this failure. Also, the type of flow is not only the main reason that caused this erosion –corrosion failure at girth welds. Actually the presence of protrusions due to the excess penetration of the root weld bead (Figs. 3&4) had made an obstruction that disturbed the laminar flow pattern and created a localized turbulent flow conditions with greater agitation and eddy movement. Metal is removed from the surface as dissolved ions, or forms of solid corrosion products, which are mechanically swept from the metal surface. Many types of corrosive mediums could cause erosion-corrosion. These include gases , aqueous solutions and organic systems. Solids suspensions in liquids are particularly destructive in of erosion-corrosion. This largely accelerates erosion- corrosion leading to failure in a relatively short time [3-8]. In addition, the high hardness values of HAZ and WM are an indication of high heat input which in turn led to the formation of coarse grains near fusion line [3]. This created a heterogeneous structure and localized thermal stresses around fusion line and HAZ, facilitating corrosion attack through this zone following the erosion-corrosion mechanism indicated above [9-12].

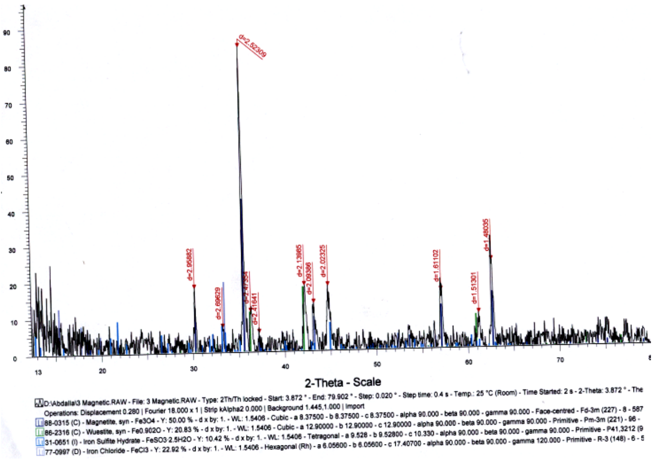

Fig. 10 Result of XRD analysis.

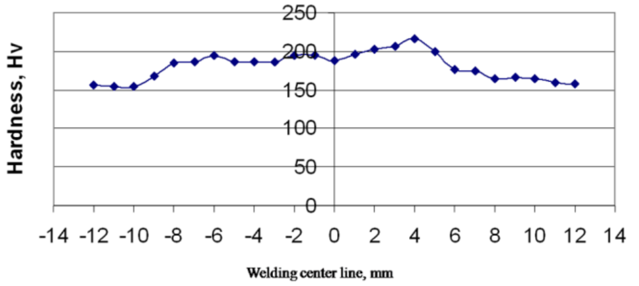

Fig. 11 Results of hardness profile of welding no. 3.

V. Conclusions and Recommendations

Based on the results obtained in this investigation, the failure of gas pipe lines could be attributed to accelerated localized erosion- corrosion attack due to improper welding operation of girth welds. Undercut, excess bead penetration of root weld bead and high heat input could be the primary causes for the localized turbulent flow conditions created around the girth weld and resulting in this accelerated erosion- corrosion failure. It is highly recommended to apply a proper welding procedure with the corresponding WPS, PQR and to be carried out by qualified welders. Special emphasis should be given to the heat input during welding process. Hardness measurements at weld metal and HAZ should be carried out. Non destructive testing should be applied after welding.

Acknowledgment

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