Journal of Innovation and Development
ISSN: 2958-4752 | Vol. 16, No. 2, 2026

Failure Analysis of Localized Corrosion Perforation of an Oil and Gas Pipeline Dominated by CO_2

Hui Wang

Shandong Haike Chemical Co., Ltd. Dongying, Shandong, 257000, China

Abstract: A systematic failure analysis has been carried out on a leaking part of an oil and gas pipeline that has suffered from internal pitting and perforation due to operation. Observe the general shape and, with the help of X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy (EDS), determine the phases, microstructure and elemental distribution of the corrosion products. Based on the above results, the main corrosion product is ferrous carbonate ($FeCO_3$), which is a typical product of CO_2 corrosion. The corrosion product layer is porous and uncompacted, and there are many through-going cracks in the cross-section; thus, it cannot protect the steel below. Impurities in the transporting medium, such as chloride ions (Cl^-), sulfides (S^{2-}), calcium salts and silicates, constantly enter through the cracks and pores of the product film to reach the metal substrate. At the corrosion front, there are all kinds of cell occlusion, under-deposit corrosion and crevice corrosion, and as a result, local wall thinning and pitting perforation have occurred. The failure of the CO_2 corrosion product film due to the combined effect of many corrosive agents will result in a local perforation, and this paper will provide a reference for controlling corrosion in similar oil and gas pipelines.

Keywords: Oil and gas pipeline; CO_2 corrosion; pitting; perforation failure; ferrous carbonate; corrosion product film.

1. Introduction

Carbon steel pipes are used in the oil and gas gathering and transmission system because they are relatively inexpensive and have good mechanical properties. However, the transporting media often have various corrosive substances such as CO_2, H_2S and Cl^-, and under multiphase flow conditions, carbon steel pipelines are very susceptible to corrosion failure. CO_2 corrosion is one of the most common types of corrosion in the oil and gas industry; it is typically localized and takes the form of pitting, mesa-type corrosion and wormhole-like attack. Corrosion in the pipeline and the resulting leakage accident are serious threats to the safety of people and property. CO_2 in water forms carbonic acid, which lowers the pH of the environment and thus causes electrochemical corrosion of steel. Corrosion products of $FeCO_3$ can form a protective film in good conditions; however, if the environment changes or other harmful ions are present in the medium, the density and stability of the $FeCO_3$ film will be greatly reduced [2-3].

In CO_2-containing oilfield production environments, there are many types of corrosive substances, such as Cl^-, S^{2-} and Ca^{2+}, that can occur together. Cl^- has a small ionic radius and is highly penetrative; therefore, it can break down the protective film of corrosion products and cause local corrosion. Sulfides (e.g., H_2S) can be added to CO_2 to increase the local dissolution of the metal [4]. At the same time, the scale-forming cations Ca^{2+} and Mg^{2+} can cause salt deposition and thus under-deposit corrosion; an occluded cell is formed under the scale layer, and further local damage occurs. The combined effect of all the corrosive factors is generally much larger than the sum of the individual effects [5-6].

Although many studies have been carried out on the mechanisms of CO_2 corrosion and failure analysis, the microscopic mechanism by which the failure of the CO_2 corrosion product film under multi-factor synergy leads to local perforation has not been well understood. The subject of this paper is a section of a perforated pipeline with internal pitting; through systematic phase analysis, microstructural observation and elemental mapping, it has been determined that the main cause of the local perforation mechanism is CO_2 corrosion under the joint action of multiple corrosive agents. Based on this, we will use it to prevent corrosion in other sections of the pipeline.

2. Experimental Methods

2.1. Sample Origin

The bad sample was taken from a leak in a part of the oil and gas transmission pipeline that was in use. There is a significant loss of wall thickness at that place, and there are many pits and holes. There is a small through-hole in the outer wall at that location, and it is not severely corroded externally.

2.2. Test Procedures

Loose corrosion products were collected from the inside of the damaged area and analysed by X-ray diffraction (XRD) to determine the phases. Test Conditions: Cu Kα radiation, Scanning Range 10°-80°, Scanning Speed 2°/min.

Samples were taken from the area of the pitting pit and perforation. Scanning Electron Microscopy (SEM) was employed to obtain pictures of the shape of the inside surface and a cross-section of corrosion products, and at an accelerating voltage of 20 kV, Energy-Dispersive X-ray Spectroscopy (EDS) was used to determine the elemental composition of a small area. A cross-section was prepared in epoxy resin, and then it was ground and polished.

3. Results and Discussion

3.1. Phase Analysis of Corrosion Products

The XRD pattern of the loose corrosion products (Fig. 1) shows that all the diffraction peaks match the standard card for ferrous carbonate ($FeCO_3$), and no other phases were found. $FeCO_3$ is a typical product of CO_2 corrosion, and its formation follows the usual reaction path: CO_2 dissolves in

water to form carbonic acid (H_2CO_3), which dissociates to release H^+ and promote anodic dissolution of iron ($Fe \rightarrow Fe^{2+} + 2e^-$); Fe^{2+} then reacts with CO_3^{2-} in the medium to precipitate $FeCO_3$. According to the XRD results, there is considerable CO_2 carbonic-acid corrosion in this section of the pipe, and CO_2 is the main cause of wall thinning.

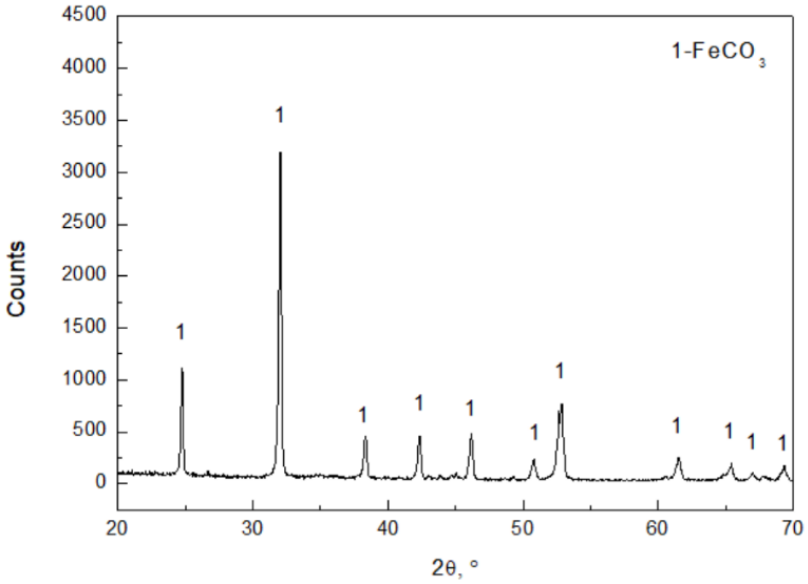


Figure 1. The XRD pattern of the corrosion products

3.2. Macroscopic Morphology

The general shape of the failed pipe section is shown in Figure 2. There is serious localised corrosion and thinning of the inner wall, and there are also areas of concentrated corrosion, distinct pitting and perforation (Fig. 2a). There is only a small through-hole at the location of the perforation on the outer wall, and otherwise, there is no serious external corrosion (Figure 2b). The general feature is that the mode of failure is an internal localised pitting perforation, and corrosion began from the inside in contact with the medium. Pitting is a typical form of localised corrosion in CO_2 environments; it is very harmful and can lead to leaks after reaching the wall.



Figure 2. The general shape of the damaged pipe

3.3. Microstructure and Composition of Corrosion Products

3.3.1. Surface Morphology and Elemental Analysis

Figure 3 is the SEM image. Corrosion products have a loose, porous structure, consisting of flaky and granular materials that are piled up, and they have developed pores and poor compactness. A loose structure is not a good physical barrier for the metal substrate, so the dense, protective $FeCO_3$ films mentioned in the literature are preferred.

As shown in Table 1, all the analysed points have high concentrations of C, O and Fe, which is consistent with the XRD results, and $FeCO_3$ is the main phase. At point 1 near the substrate, the atomic proportion of Fe is as high as 68.44%,

and C and O are relatively low; thus, the corrosion layer at the metal-substrate interface is thin. Points 2 and 3 on the outer surface have C contents of over 54% and much lower Fe; thus, they are enriched with pure $FeCO_3$ at the outside. Point 4 has a relatively high amount of Ca (11.37 at%) and some trace amounts of Na, Mg, Sr, Ba, S and Cl. Ca shows that there are calcium salts in the medium, and S and Cl are present as trace sulfides and chloride ions; these are typical impurities in formation water. Notably, Cl^- is one of the reasons for pitting and accelerates the breakdown of the protective film.

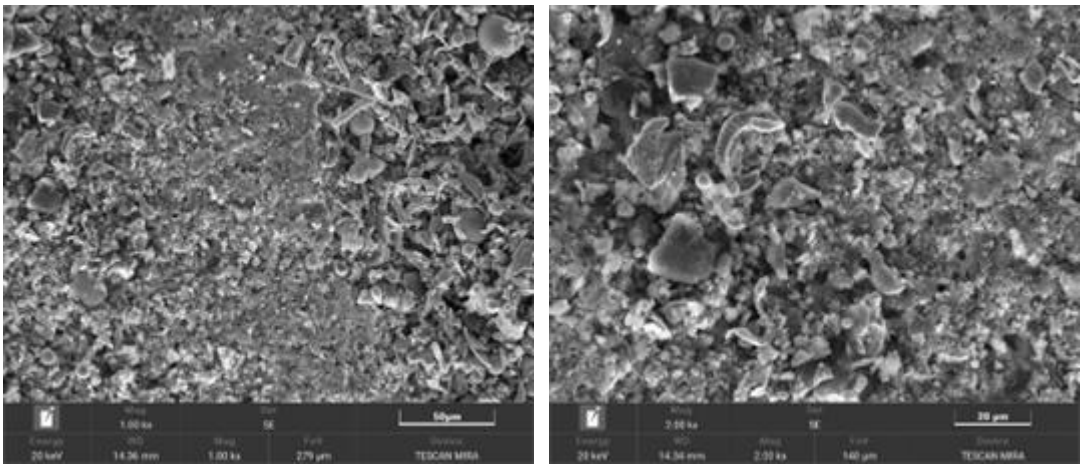


Figure 3. The general shape of the damaged pipe.

Table 1. EDS Elemental Analysis of Inner-wall Corrosion Products (at%)

Element	Spectrum1	Spectrum2	Spectrum3	Spectrum4
C	18.13	54.04	55.73	44.54
O	11.58	-	10.29	21.46
Na	-	-	-	1.74
Mg	-	-	-	0.68
Si	0.81	0.29	0.30	0.62
S	-	-	-	0.42
Ca	0.18	0.21	0.21	11.37
Mn	0.85	0.35	0.31	0.31
Fe	68.44	45.11	33.03	16.86
Sr	-	-	-	1.84
Ba	-	-	-	0.16

3.3.2. Cross-sectional Morphology and Elemental Mapping

Figure 4 is the cross-section shape of the corrosion area and the corresponding EDS element maps. The three parts in the cross-section, from bottom to top, are: the steel substrate (light grey and dense), a thick corrosion product layer (dark grey and loose), and an embedding epoxy (black). There are many transverse and longitudinal cracks and voids in the corrosion product layer, and the film integrity is very poor. There are cracks and pores through which corrosive agents can enter from the inside. Corrosive agents constantly move through the cracks and pores to cause severe erosion at the edge of the substrate, and this is one of the main reasons for continuous pitting.

EDS mapping shows that: the Fe signal is relatively strong in the substrate area and relatively uniform in the corrosion product layer, indicating that iron is distributed throughout the corrosion products; at the crack location, the Fe signal is weaker, and it can be inferred that the metal substrate has been consumed first. The C and O signals fully cover the corrosion product layer but are almost absent in the substrate, indicating that the corrosion layer consists of iron salts containing carbon and oxygen (ferrous carbonate), and CO_2 is the main corrosive agent. The C and O enrichment zones are located at the crack sites, so a continuous supply of carbon source has reached the cracks and the corrosion reaction is still ongoing.

Cl^- is distributed unevenly in the cracks and pores of the corrosion product layer; it is not spread uniformly over a large area but tends to accumulate at the corrosion interface and crevices. Cl^- has a small radius and strong penetrating power, so it can break up the $FeCO_3$ film and cause local pitting; it is a serious reason for perforation in this case. S is distributed in bands along the transverse cracks of the corrosion layer, and it has been found that trace sulfides (H_2S or other sulfides) are present in the environment. Sulphides will cause local galvanic corrosion and increase the corrosion crevice in the presence of CO2. Ca is concentrated in the middle-upper part of the corrosion product layer and shows a banded distribution; it originates from calcium salts in the water that form carbonate scale. The scale layer is not thick, but there can be an occluded cell below that leads to under-deposit pitting. Si is a discrete spot-like impurity that originated from sand or silicate particles in the medium.

Generally speaking, cross-sectional analysis shows that the corrosion product layer is a loose, composite film mainly composed of $FeCO_3$ and calcium scale, along with trace amounts of sulfides, chlorides, silicates, etc. The cracks in the product film are the main paths for aggressive ions (Cl^-, S^{2-}) and CO_2 to reach the substrate.

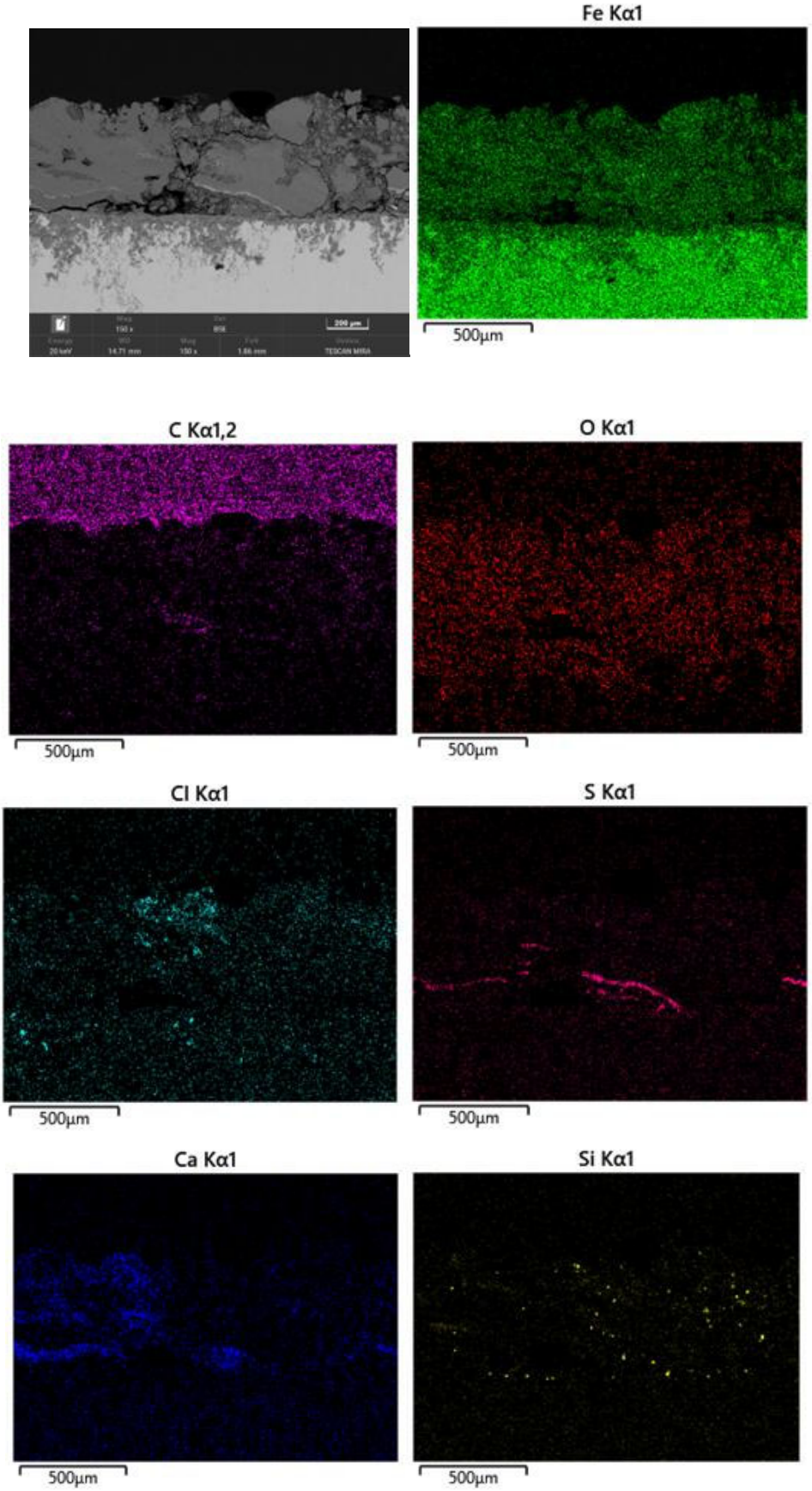


Figure 4. Cross-sectional Morphology and Elemental Mapping

3.4. Corrosion Mechanism Analysis

Based on the characteristics mentioned above, the mechanism of corrosion-perforation in this case can be summarized as follows: The pipeline is carrying a medium containing CO_2 and formation water. CO_2 dissolves in water to form carbonic acid, which then causes electrochemical corrosion of the carbon steel and produces $FeCO_3$ as the corrosion product. Although a dense film of $FeCO_3$ should ideally offer some protection to the substrate, in this case, the corrosion product layer is porous and full of through-going cracks; thus, it cannot function as a barrier. The poor compactness may be due to the presence of aggressive ions such as Cl^- and S^{2-} in the medium; -Cl^- can disrupt the crystal structure of $FeCO_3$, and S^{2-} can alter the film properties.

Due to the defective film, Cl^-, S^{2-} and other aggressive ions continuously move through the cracks to the metal substrate and form an occluded cell at the corrosion interface. Metal dissolution occurs in the occluded cell, hydrolysis of Fe^{2+} reduces the local pH, and as a result, anodic dissolution is further promoted by self-catalysis. Ca^{2+} precipitates as carbonate scale in the upper part of the corrosion product layer. It is not very dense, but there will be some local occlusion and thus under-deposit corrosion. Under-deposit corrosion, crevice corrosion and occluded cell effect are synergistic, have a very high local corrosion rate compared to uniform corrosion, thus damage occurs at the pitting site of the pipe wall and leakage occurs.

Notably, the corrosion is concentrated on the inner wall, and the outer wall remains almost intact; thus, it can be concluded that the driving force for corrosion is internal and not external, and this failure mode is typical of medium-side corrosion perforation.

4. Conclusions

(1) The corrosion products of the failed pipe section are predominantly ferrous carbonate ($FeCO_3$), a characteristic product of CO_2 corrosion, confirming that CO_2 is the core corrosive agent responsible for wall thinning.

(2) The corrosion product layer is loose and porous, with numerous through-going cracks in cross-section; its poor compactness fails to protect the metal substrate. The structural defects of the product film are the fundamental reason for the continuous corrosion development.

(3) Impurities in the transporting medium, including Cl^-, S^{2-}, and Ca^{2+}, penetrate continuously through the cracks of the product film towards the substrate, where the synergistic action of occluded cell formation, under-deposit corrosion, and crevice corrosion greatly accelerates local wall thinning, eventually leading to pitting perforation.

(4) The synergistic effect of multiple corrosive factors is the key reason for the relatively rapid perforation failure of this pipeline in service. In practical engineering, special attention should be paid to aggressive components such as Cl^- and S^{2-}, as well as scale-forming ions, and appropriate corrosion control measures should be adopted.

References

[1] Kahyarian, A., Brown, B., & Nesic, S. (2017). Electrochemistry of CO_2 corrosion of mild steel: Effect of CO_2 on iron dissolution reaction. Corrosion Science, 129, 146-151. https://doi.org/10.1016/j.corsci.2017.10.013.

[2] Fu, A. Q., Yuan, J. T., Li, X. P., et al. (2021). Gathering pipeline corrosion of oil and gas field and its anti-corrosion technologies. Petroleum Tubular Goods & Instruments, 7(6), 14-25, 32.

[3] Xu, Z. D., Yang, Z. N., Li, W. T., et al. (2022). Failure analysis of corrosion and perforation of N80 tubing in an offshore water injection well. Chemical Equipment Technology, 43(3), 48-52.

[4] Cai, R., Wu, P., Zhao, J. L., et al. (2019). Corrosion failure analysis of L245 gathering pipeline. Surface Technology, 48(5), 58-64. https://doi.org/10.16490/j.cnki.issn.1001-3660.2019.05.009

[5] Liu, X. L., Wang, Z., & Cui, X. H. (2019). Causes analysis of corrosion and perforation of production meeting pipelines in a united station in Tarim oilfield. Materials Protection, 52(1), 123-128, 139.

[6] Xu, Y. Y., Ge, P. L., Gao, D. L., et al. (2019). Failure analysis of certain water injection pipeline. Materials Protection, 52(11), 162-165.