IBP1173_09

LEAK IN SPIRAL WELD IN A 16" GAS PIPELINE

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Abstract

This paper discusses a Failure Analysis after a leak in the spiral weld of a 16" natural gas pipeline, in service since 1974. The leak was the result of the coalescence of two different defects, on each surface of the pipe wall, located in the center of the inner cord of the helical DSAW weld. Fractographic and metallographic studies revealed that the leak was a combination of three conditions. During fabrication of the pipe, segregation in grain boundary grouped in mid weld. During service, these segregations underwent a process of selective galvanic corrosion. One of these volumetric defects coincided with a tubular pore in the outer weld. Pigging of the pipeline in 2005 for cleaning likely contributed to the increase of the leak flow, when eliminating corrosion product plugs. Although these defects are likely to repeat, fracture mechanics shows that a defect of this type is unlikely to cause a blowout.

1. Introduction

This study establishes the causes (operative, maintenance, materials, design, construction, etc.) that produced a leak in the spiral weld of a 16" diameter, 6,35 mm thick natural gas pipeline, in service since 1974. The pipe operates at 68 Bar inner pressure. Last hydrostatic test and internal inspection of the section was conducted in 2005, leaks or defects were not reported then in the affected sections. The defect that produced the leak was located in the center of the inner cord of the helical DSAW weld, **Figure 1**. The leak was signalized by a small wire.

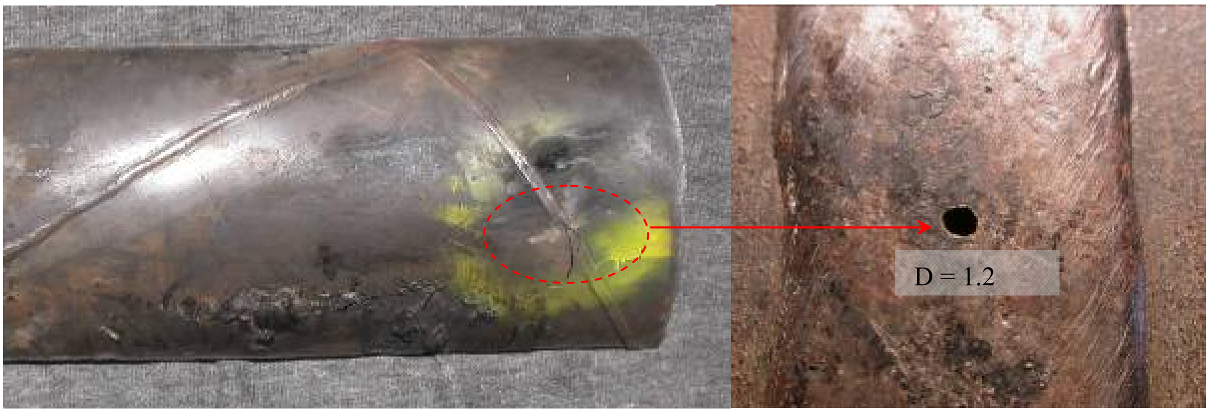

Figure 1: Defect that produced the leak and leak detail, external surface

The pipeline was constructed with API 5L X52, 16" diameter, 6,35 mm thick pipes, and in this section operates with an internal pressure of 68,4 Bar. Initiation of service dates back to 1974, year of the last Hydrostatic Test. In the internal inspection conducted in September of 2005, defects in the pipe at issue were not reported.

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In a first analysis, apparently a 1.2 mm wide pore at mid weld of the spiral seam weld generated the gas leak, Fig. 1. The determination of the mechanism by which the leak took place is fundamental for the prevention of future failures, since necessary corrective measures can be taken only after root causes are understood. This failure analysis [1] aims to: a) identify operating failure mechanisms; b) determine the causes that created the conditions so that this mechanism generated the failure; c) establish the probability and future failures on similar components d) evaluate possible mitigation actions.

On the outer side, the leak is circular, Fig. 1. Of the inner surface, however, the leak is elliptical, approximately 7 mm long and 1,5 mm wide. **Figure 2** shows its location in the weld and the position of the weld with respect to the gas flow. Longitudinal marks are likely due to passage of an internal tool. Some oxide deposits in the inner surface of the tube were mechanically removed.

Other defects along this weld were also detected, although smaller, that have similar characteristics (details A, B in **Figure 3,** after surface cleaning), Greater detail of the leak (inner surface) is shown in **Figure 4**. The dotted indicates the cut made for the metallographic sample. Defect characteristics are similar to a cavern, within which a pair of "tunnels" exists. One of those tunnels ends across of the weld, in the orifice indicated in Fig. 1.

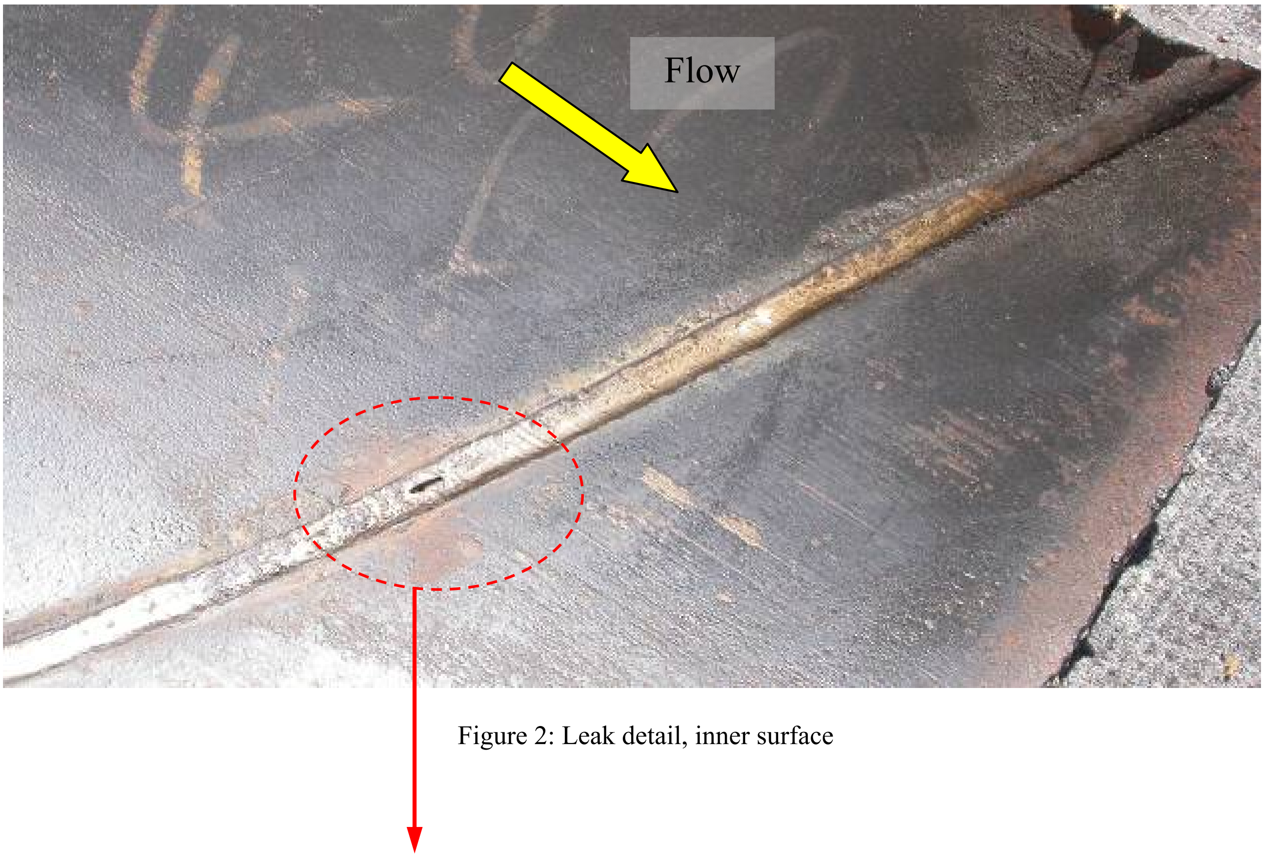


Figure 2: Leak detail, inner surface

Figure 3: Other defects along the weld

Figure 4: Greater detail of the leak

2. Metallographic, Chemical and Mechanical Tests

Interaction between defects and microstructural characteristics of the material was analyzed via polished and Nital etched cross sections. **Figure 5** shows a metallography of the section indicated in Fig 4. The weld is a double submerged arc process. The inner bead presents evident discontinuities, probably due to selective corrosion from nonmetallic inclusions or segregations, which were trapped in weld metal. The volume originally occupied by these inclusions eventually became caverns or hollows. Note that one of these segregations stops exactly in the inferior part of the outer weld bead.

The microstructures of both weld beads are different. The outer bead shows a oriented structure with a well defined Heat Affected Zone (HAZ). The inner bead shows a fine microstructure with a smooth, almost imperceptible, transition to base material. This difference is product of the weld sequence. The outer bead was laid after the inner bead, which this way underwent a heat treatment.

The same characteristics are seen registered in the cross section at the leak, **Figure 6**. In this case, the volumetric discontinuity connects the inner surface with the outer one. Note that the cut is normal to the surface and the discontinuity or "tunnel" is slightly inclined.

Figure 7 (X500), shows the microstructure at the center of the outer bead and its relation with the through defect. The edges of the defect do not display a clearly identifiable microstructural characteristic. **Figure 8** (X500) on the other hand, shows the characteristics of the edges of the cavern in the inner bead, compatible with an initial slag inclusion. These details allow verifying the existence of a process of selective corrosive, caused by a chemical agent from the inner side of the pipeline.

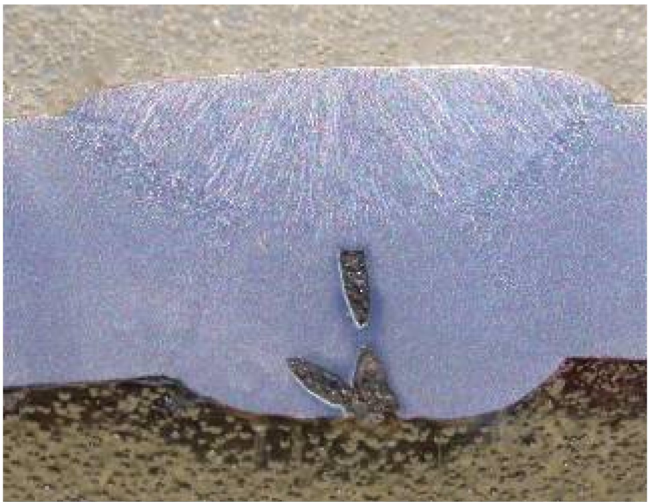
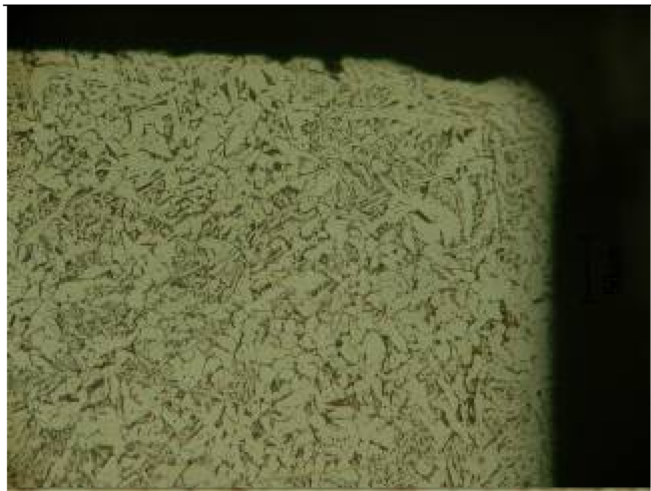


Figure 5: metallography of the section indicated in Fig 4

Figure 6: cross section at the leak



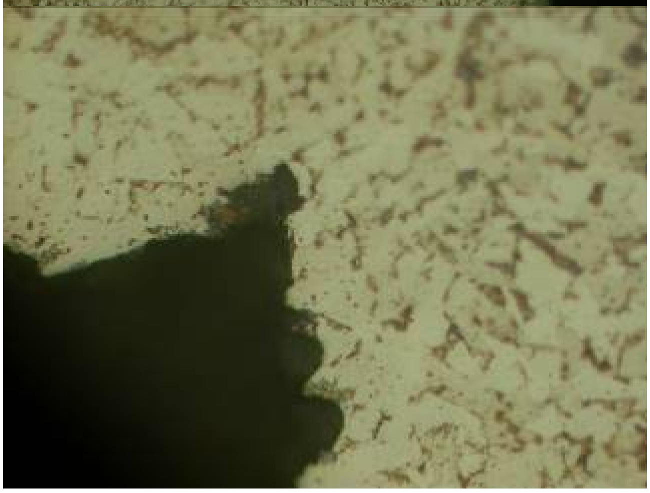


Figure 7: (X500) microstructure of the outer bead

Figure 8: (X500) characteristics of the inner bead

For a process like this to occur, a difference in electrochemical potential between the material of the corroded zone and that of the surrounding material is needed. Also, a corrosive agent is needed in the transported flow. Both conditions were analyzed by means of chemical analyses.

Scanning electron microscopy and EDS analyses of chemical composition were carried out. In the material filling the discontinuity at the inner weld some nonhabitual elements, like Aluminum, Silicon, Sulfur, Chlorine and Calcium are seen in **Figure 9.** Likely, Cl is due to cleaning of samples, the other elements are due to weld metal alloying.

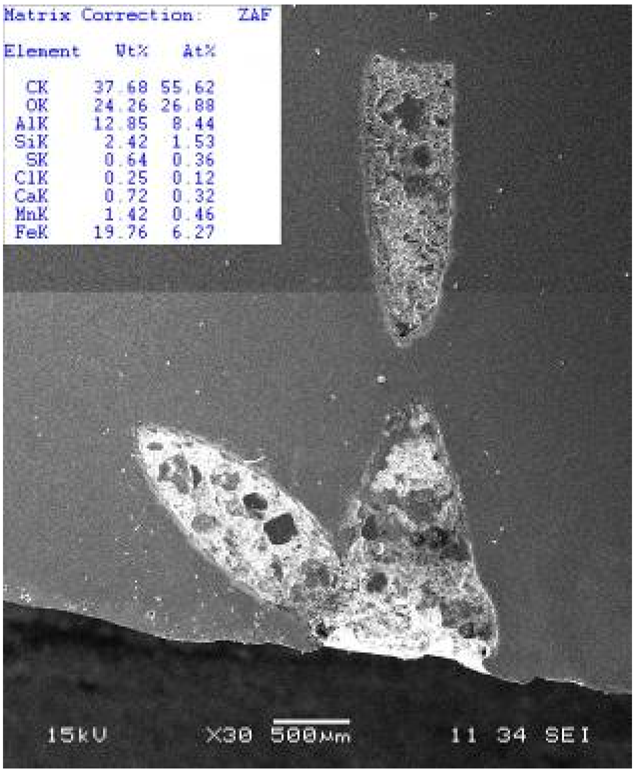


Figure 9: EDS analyses of chemical composition

Table 1: Base metal chemical analyses and API requirements

Source	Elements							
	C	Si	Mn	P	S	Cr	Ni	Mo
Base metal	0.19	0.010	1.02	0.018	0.010	0.03	0.01	0.01
API 5L X52 (% max)	0.22	-	1.40	0.025	0.015	-	-	-

Micro hardness mapping did not reveal hard spots, hardness values average below 20 HRC, normal for this type of pipes. Ultrasonic testing over the entire affected pipe allowed rescuing a section without discontinuities. Mechanical tensile and Charpy tests were carried out in material from these regions, see **Table 2**. Tensile rupture was always in base material, confirming that, in absence of discontinuities, the weld has excellent properties.

Table 2: Mechanical tensile properties

Elongation (%)	22
Reduction of Area (%)	52
Fracture stress (MPa)	554

Charpy results were correlated with Kic fracture toughness. The average Kic for the weld is 100 Mpa $m^{1/2}$, considered very good for a weld made more than 30 years ago. This value was then used to assess a critical defect size.

3. Mechanical Modelling

The risk of a bow out from a defect such as the one that lead to this leak was assessed. When the toughness of the materials is relatively low, the behavior of a component under cuasi-static conditions of load can be modeled by means of linear elastic fracture mechanics (LEFM) [2]. For a relatively tough material, as is this case, fracture would occur after an important amount of plastic deformation. For this case API RP 579 "Fitness for Purpose" [3] procedures recommend the use of the Failure Analysis Diagram (FAD).

For a buried pipe under internal pressure, Barlow equation gives a close approximation to the actual circumferential component of the stress field at the failed weld. The longitudinal stress is usually considered from the condition of zero deformation along the pipe axis, considering the restriction to the displacement by the surrounding soil. The resulting expressions are:

$$\sigma_C = \frac{p.\Phi}{2.t} \qquad\qquad \sigma_L = \upsilon.\sigma_C \approx \frac{\sigma_C}{3} \tag{1}$$

Where p is the inner pressure, Ø pipe diameter, t thickness, ν Poisson module, and the components of σ represent circumferential and longitudinal stresses. Since the angle of the spiral weld is 45°, the longitudinal stress component normal to the weld, and therefore normal to the fracture surface, is easily considered from the Mohr circle. The resulting normal stress is σ_h = 145 MPa, this is, 2/3 of the hoop stress (217 MPa).

Arc welds with double -V joints develop residual tensile stresses, depending on weld conditions and previous and later treatments. According to tests made in other similar components [4] residual stress in the transverse direction to the weld bead is around 50% of yield strength, that is, 180 MPa.

Crack tip stress intensity for the defect being assessed is calculated by means of the expression:

$$K = Y.\sigma.\sqrt{\pi.a} \tag{2}$$

Material fails when K reaches K_{IC}, the toughness for the material, defined as 100 MPa√m. Considering stress components due to pressure (145 MPa), and residual (180 MPa), we have total a static stress of 325 MPa. In order to simplify the problem, consider the criticality of a through the thickness defect, with Y = 1, the overall length of the largest corrosive defect in the inner surface is: 2a = 7 mm. In this way an applied crack driving force is:

$$K = (180 + 145).\sqrt{\pi.0.0035} = 32MPa\sqrt{m}$$

We see that in these conditions it is not possible to justify the propagation of a blow out from the through defect. The stress applied to the section for the case of plastic collapse is defined by the equivalent stress. Here the residual stress is not considered [5] , so that for such a small defect, the applied stress is about 330 MPa. For a yield stress of 440 MPa, we can define a flow stress rate according to API 579:

$$\sigma_f = SMYS + Ksi = 440 + 70MPa = 510MPa$$

The stress ratio is defined

$$S_r = \frac{\sigma_{VM}}{\sigma_f} = 0.65$$

The parameter FAD describes the interaction between fracture and plastic collapse. Stress and driving force ratios, Sr and Kr, are therefore defined as:

$$K_r = \frac{K_{eff}}{K_I} \qquad \text{and} \qquad S_r = \frac{\sigma}{\sigma_C}$$

The FAD of **Figure 10** shows the site of predicted failure. All points inside the FAD are considered safe; points outside the diagram are unsafe. The square point (Sr. = 0.65, Kr = 0.32) corresponding to the analyzed defect falls in the safe part of the diagram, far from limits of admissibility.

The round symbol indicates a certain risk of fast fracture or blow out. This condition is reached when Kr = 0.72. The length of a through defect for this condition, as calculated with eq. 2, is around 30 mm.

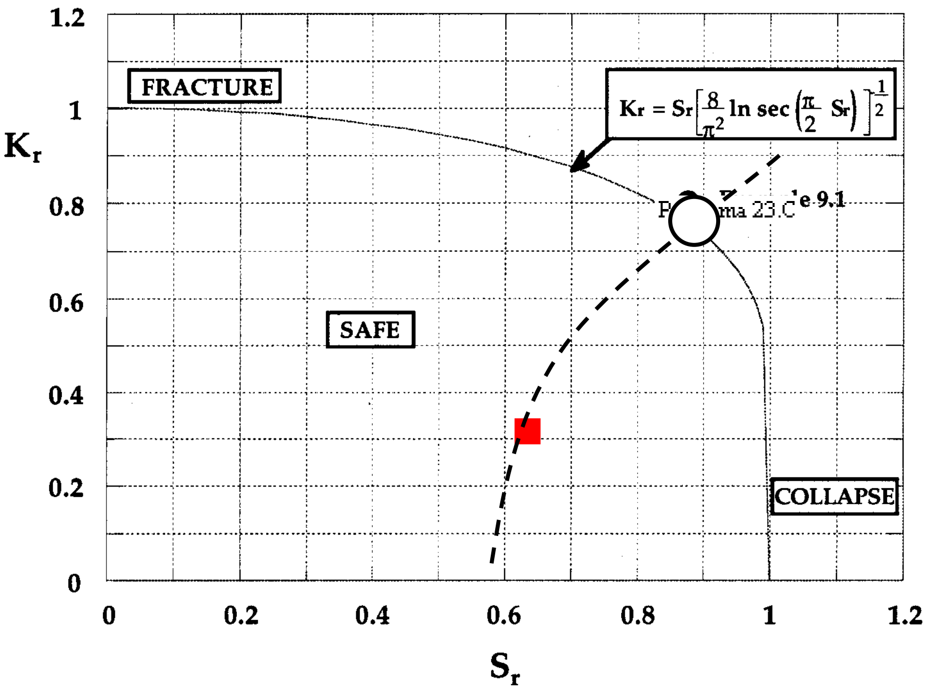


Figure 10: Fad diagram

4. Discussion of Results

Defects such as lack of fusion, slag inclusions, hot and cold cracking, porosity, are common in DSA welds. **Slag inclusions** are solid nonmetals caught in weld metal or between weld and base metals. These inclusions are inherent to the weld technique, mainly due to inadequate cleaning between passes. Normally, dissolved slag flows out of the molten metal, but with old consumables inclusions frequently are trapped in weld metal. This it is the case of the defects seen in the inner surface of the spiral weld. Some sectors present signs of selective corrosion at those spots.

Also, impurities generate segregations during weld solidification. These defects are associated to weld metallurgy, arc protection and surface cleaning. Segregations are islands of different composition than the rest of the metal, at boundaries of columnar grains in weld metal. One of the most pernicious forms of segregation is in the center of the bead [6]. This it is the case of the defect on the inner surface, Fig. 4, 5, 6. Pores seen in the outer weld bead are also typical discontinuities in these welds. A particular case of pore is wormhole (tubular pore), when trapped gas is caught half way out.

Fractographic and chemical evidence allows concluding that in-service selective galvanic corrosion of segregation defects in the inner weld bead combined with some erosive process by gas the flow, generated extended caverns in the inner pass of the weld, which evidently stopped when reaching the material of the outer bead (Fig. 5). One of these volumetric defects, however, coincided with the location of a tubular pore in the outer bead, thus giving way for the leak, Fig. 6.

Further corrosion and erosion eventually increased the volume of the leak. Cleaning of the pipe with a scraper also contributed to the increase of leak flow, when eliminating corrosion product that clogged the leak and also perhaps accelerating corrosion rate.

Many other discontinuities of this type in the pipeline are most probable. The critical length of a surface defect of this type to cause a blow up is more than 30 mm, Fig. 10. No defects this size have been reported by ILI and other exploratory direct inspections. However, these defects will always lead to leaks. Therefore, this study showed that the affected pipes are in a leak before break condition.

5. Conclusions

Several defects in the DSAW spiral seam weld were detected, although only one lead to a leak. Fractographic and metallographic studies revealed that the leak was a combination of three conditions. Two of these conditions were found in many places along the weld bead on the pipe tract. During fabrication of the pipe, segregation in grain boundary grouped in mid weld. During service, these segregations underwent a process of selective galvanic corrosion, possibly combined with some erosive process due to the gas flow.

In most of the sections, the corrosion stopped when reaching the outer weld bead. One of these volumetric defects coincided with the location of a tubular pore in the outer weld. The pore was enlarged by the same corrosion and erosion process, with which the volume of the leak was increased with time.

Pigging of the pipeline in 2005 for cleaning likely contributed to the increase of the leak flow, when eliminating corrosion product plugs. Although these defects are likely to repeat, fracture mechanics shows that a defect of this type is unlikely to cause a blowout.

7. References

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