ASSESSMENT OF PREMATURE DEGRADATION OF A GAS INJECTION PIPELINE DUE TO HYDROGEN RELEASED BY THE BENZENE HYDROFINING EQUIPMENT

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The present research aimed to identify the causes that led to the deterioration of a pipeline comprised in the benzene hydrofining equipment of a refinery. The pipeline ascending branch was perforated, therefore the installation was stopped in order to remove it and replace it.

To find the causes of the premature degradation the following investigations were performed: macroscopic examination of the pipe elbow, chemical composition, microstructure and hardness, analysis of the porosity zone from the welded joint, analysis of corrosion products deposit samples taken from inside the pipe by X-ray fluorescence and X-ray diffractometry, assessment of the different corrosion processes affecting the pipeline.

Keywords: steel, degradation, pipeline, refinery

1. Introduction

The purpose of this paper is to establish the causes that led to the deterioration of a pipeline comprised in the benzene hydrofining equipment of a refinery that ensures hydrogen gases injection in the stream of the effluent coming from the reactor. The pipeline was punctured; following the incident it was necessary to stop the installation, to inspect the faulty area and to replace the entire pipeline ascending branch, downstream from the pressure regulating valve.

In the nominal operating mode of the installation, the fluid passing through the pipeline has a pressure of 60 bar and a temperature of 100°C. The pipeline comprises a descending curved branch with successive section reductions from DN150 to DN50, a pressure regulating valve and an ascending curved branch with increasing section from DN50 to DN150 (Fig. 1). The descending branch is made of SA-106 Grade A non-alloy steel and the ascending branch is made of SA-335 Grade P11 alloy steel [1].

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Fig. 1. The aspect of the pipe in the installation

Fig. 2. Aspect of the area where the crack occurred

For the present study samples were taken in order to perform material analyses and also those made in order to establish the corrosion type. For this purpose, a section comprising the damaged area was extracted from the pipeline. The aspect of the pipe zone where the porosity responsible for the incident was located is shown in Fig. 2.

The following investigations were performed:

- macroscopic examination of the pipe elbow section showing a porosity and products sampling from the pipe inner surface;
- analysis of the pipe material quality - chemical composition, microstructure and hardness - followed by results comparison of the same features with these of the material standard prescribed by the project;
- analysis of the porosity zone from the welded joint, namely macrostructure, microstructure and hardness;
- analysis of corrosion products samples taken from inside the pipe by X-ray fluorescence and X-ray diffractometry.
- assessment of the different corrosion processes that affected the pipeline.

2. Tests and investigations

The testing program included chemical and metallographic analyses, mechanical testing, as well as analyses by optical microscopy, X-ray fluorescence technique and X-ray diffractometry.

2.1. Macroscopic analysis

Aspect. The analyzed section of the pipeline, representing its ascending branch, is shown in Fig. 3 and contains the welded subassembly consisting of DN50 pipe, DN100 / DN50 eccentric reducer, DN100 pipe elbow and DN150 / DN100 eccentric reducer. One may observe that a different constructive solution was applied to the execution of the subassembly than the one shown in Fig. 2, namely hot formed reducers were used instead of cone - cylinder welded reducers. The porosity indicated in Fig. 3 is located in the welded joint between the eccentric reducer DN100 / DN50 and the pipe elbow DN100.

Fig. 3. Locating the pipeline fault, face 1 and face 2

After external examination of the failed pipeline section, the following were noted:

- the outer metal surface of the part is relatively clean, free of signs of corrosion indicating significant loss of thickness;
- the welded seams between the components are wide and prominent as compared to the components wall thicknesses;
- in the maximum radius of curvature zone of the DN100 pipe elbow the piece shows recent traces of polishing; on the pipe elbow's side there is a written mark, probably applied after the failure;

Inside the pipe the metal surface shows pronounced signs of general and pitting corrosion [2], including the welded seams areas, as seen in Fig. 4. The surface of the metal is mostly covered with dark deposits. The exception is the DN100 / DN150 reducer area, which, in the part corresponding to the large radius of curvature, shows deposits in the form of thin, reddish crusts. Samples were taken from each differently coloured deposition for analysis.

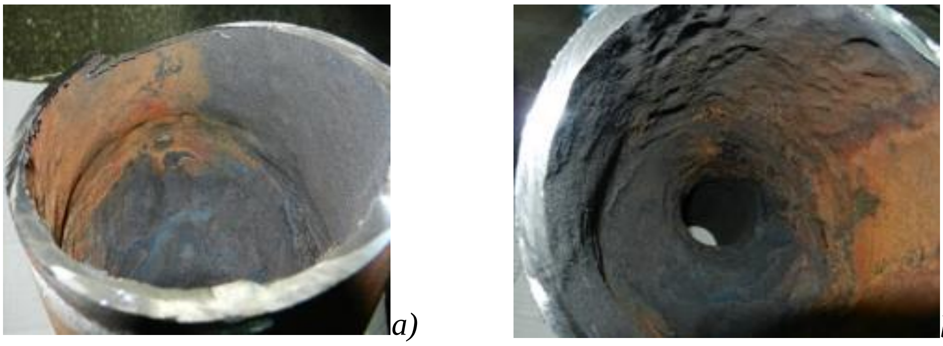


Fig. 4. Aspect of the pipeline coupon inner surface, with views in the low radius of curvature direction (a) and in the high radius of curvature direction (b)

Dimensions. The wall thicknesses of the pipeline upper branch components were determined by means of nondestructive testing. After removing the pipeline coupon from the installation and sectioning it for analysis, direct measurements of the outer diameters and wall thicknesses were also performed. The obtained results are summarized in Tables 1 and 2 [2].

Regarding the components outer diameters when compared to the nominal dimensions, these are in the tolerated range or have small positive or negative deviations, in the immediate vicinity of the limit values allowed according to ASME SA-335 [1]. This is important for the analysis of the deterioration processes that have influenced the operating behavior of the pipeline.

Table 1

Outer diameters of the components being part of the pipeline coupon, mm

No.	Component	Nominal dimensions, mm [3]	Allowed limit values, mm [3]	Measured values, mm
1	Pipe DN50	Φ 60 ± 0.40	59.6...60.4	59.9...60.8
2	Eccentric Reducer DN100/DN50	Φ 114 + 1.59/-0.79	113.2...115.6	112.8...113.0
		Φ 60 ± 0.40	59.6...60.4	59.5...60.0
3	Pipe Elbow DN100	Φ 114+ 1.59/-0.79	113.2...115.6	114.4...115.0
4	Eccentric Reducer DN150/DN100	Φ 166+ 1.59/-0.79	165.2...167.6	169.3...170.8
		Φ 114+ 1.59/-0.79	113.2...115.6	113.3...114.6

Table 2

Wall thicknesses of the components being part of the pipeline coupon, mm

No.	Component	Nominal dimen- sions, mm	Allowed limit values, mm	Determination US	Measured values (after sectioning), mm
1	Pipe DN50	Φ 60×6.0	5.4...6.6	1.9... 5.6	4.3...5.1
2	Eccentric Reducer DN100/DN50	Φ 60×6.0	5.4...6.6	3.3... 11.7	2.5...14.5
		Φ 114 ×8.0	7.2...8.8	3.8... 7.2	0.8...4.0
3	Pipe Elbow DN100	Φ 114×8.5	7.7...9.3	2.9...5.3	3.2...4.5
4	Eccentric Reducer DN150/DN100	Φ 114×8.0	7.2...8.8	5.7...5.9	4.8...5.7
		Φ 166×10	9.0...11.0	5.3...6.3	6.9...7.3

With regard to the tolerances, ASME SA-335 does not make direct reference to wall thickness, stating only that the inside diameter does not deviate by more than ± 1% from the specified value. Consequently, a tolerance of ± 10% of the nominal value was considered for the results interpretation, this tolerance being commonly accepted in pressure pipes.

The following observations are to be made:

- regardless of the measurement methods, it is obvious that wall thicknesses have suffered sharp decreases in all the components of the pipeline ascending branch, as against the pipeline descending branch, whose thickness is in the range 6.9 ... 10.1 mm;

- the high values of the DN50 / DN100 reducer thickness of up to 14.5 mm as against to nominal 6.0 mm in the area of the DN50 pipe joint are noticeable; these were related to the unusual shape of the reducer (see Fig. 3) and the production technology of this part; in the area corresponding to the pipe GH-120-201 minimum radius, where the damage occurred, it is assumed that the eccentric deformation of the semi-finished product and the curvature made in order to bring its diameter to 114 mm were made with difficulty and could generate from the start an insufficient wall thickness of the semi-finished product; these issues raise concerns about the initial dimensions of the DN50 / DN100 eccentric reducer.

2.2 Material quality analysis

The pipeline project specifies the manufacturing of its ascending branch from "hot rolled seamless steel pipe for high temperatures". Tubular products according to ASME SA-335 Grade P11 were used for repairing [1].

Chemical composition.

The chemical composition analysis results of the pipeline coupon four components are given in Table 3.

Table 3

Chemical composition of PPGH-120-201 pipe components, %

No.	Component	C	Si	Mn	P	S	Cr	Mo
	ASME SA-335 Gr. P11	0.05 … 0.15	0.50 … 1.0	0.30 … 0.60	max. 0.025	max. 0.025	1.00 … 1.50	0.44 … 0.65
1	Pipe DN50	0.06	0.23	0.53	0.010	0.037	0.61	0.40
2	Eccentric Reducer DN100/DN50	0.16	0.23	0.54	0.008	0.037	0.66	0.41
3	Pipe Elbow DN100	0.10	0.22	0.36	0.016	0.021	0.75	0.46
4	Eccentric Reducer DN150/DN100	0.12	0.23	0.54	0.008	0.037	0.63	0.40

One may notice that the materials of the four components do not fall within the stipulations of ASME SA-335 for P11 steel grade, as a result of the recorded deviations in the Cr, Mo and S contents.

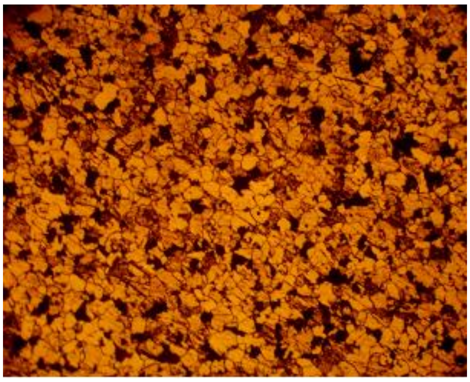
Considering the Cr contents found, the materials can be assigned to the P2 steel grade of ASME SA-335, falling within the interval 0.50… 0.81%. However, even in this case, the materials of the four components do not comply with the stipulations of ASME SA-335 concerning the Mo content, located arround or below the prescribed limit of 0.44% and the S content which, in three of the four components, is significantly higher than the maximum tolerated limit.

Microstructure. The investigation method complied with the specifications of ASME E 381. The metallographic structures of the pipeline coupon four parts materials are shown in Fig. 5.

ASME SA-335 prescribes the use of products in a heat-treated state, by normalizing and soft annealing (subcritical). The normalizing will achieve a regenerated structure after the previous processing, made of ferrite and pearlite with a high degree of fineness. The essential condition is that the heat treatment parameters are strictly kept, so that the resulting structure has the degree of fineness indicated by the norms. Subcritical annealing, in addition to the stress - relieving effect, will secondarily determine a slight globulization tendency of the pearlite. Taking into account the pipeline working conditions, the minor decrease in hardness generated by the partial globulization phenomena will not affect the good functionality of the subassembly [4]. If the corrosive action of the fluid circulating through the pipeline is also taken into account, the structure is even considered to be optimal, because the globular pearlite has a higher corrosion resistance than the lamellar pearlite. In this case, the optimal compromise between hardness and corrosion resistance must be admitted, the whole subassembly being submitted to complex requirements in operation, namely to abrasion-erosion-corrosion phenomena by the circulating fluid.

Optical microscopy investigations have shown that the DN50 pipe (Fig. 5a) and the DN50 / DN100 eccentric reducer (Fig. 5b) are not compatible with the prescribed treatment, being structures corresponding to normalizing only. However, the DN100 pipe elbow (Fig. 5c) as well as the DN100 / DN150 eccentric reducer (Fig. 5d) have structures in accordance with the indicated heat treatment. Concerning the eccentric reducer in Fig. 5d, an increased grain size is noticed, which suggests that the normalizing heat treatment (prior to subcritical annealing) did not strictly kept to the working parameters, which did not generate a proper grain size fininess, in accordance with the required norms.


a)


b)


c)


d)

Fig. 5. Optical microstructures of the pipeline components (Nital reagent, ×100): a) DN50 pipe, ferrite and pearlite, structure with fine grain size, score 8 according to SR ISO 643, corresponding to a normalizing heat treatment; b) eccentric reducer DN50 / DN100, ferrite and pearlite, structure with fine grain size, score 7-8 according to SR ISO 643, corresponding to a normalizing heat treatment; c) pipe elbow DN 100, ferrite and pearlite with a medium globulization tendency, structure with fine grain size, score 8 - 8.5 according to SR ISO 643, corresponding to a normalizing and sub-critical annealing heat treatment; d) reducer DN100 / DN150, structure consisting of ferrite and pearlite with a slight globulization tendency, but with a medium grain size, score 5 according to SR ISO 643: the structure corresponds to a normalizing and subcritical annealing heat treatment, but the normalizing exceeded either heat treatment temperature, or the holding time.

As a general observation, the four components' microstructures are different in terms of structure, but also in terms of grain size, which may be due to the microstructural features of the used products, as well as to the applied manufacturing technologies. It is assumed that the DN50 pipe and the DN100 pipe elbow were made of hot rolled pipe, because the configuration with an angle of 90° cannot be achieved by another technology, while the DN50 / DN100 and DN100 / DN150 eccentric reducers were made by a hot deformation technique involving changes in the walls thickness.

Vickers Hardness. The results of the measurements are given in Table 4.

Table 4

Mechanical characteristics of the pipeline material

No.	Component	R_m - 20°C, N/mm^2	Vickers Hardness, HV10	
			Individual Values	Average Values
	ASME SA-335 Gr. P11	min. 415	min. 127	min. 127
1	Pipe DN50[1)]	561.5[1)]	175; 177; 172	174.7
2	Eccentric Reducer DN100/DN50	507.0[1)]	157; 158; 157	157.3
3	Pipe Elbow DN100	460.0[1)]	145; 144; 137	142.0
4	Eccentric Reducer DN150/DN100	542.0[1)]	165; 169; 168	167.3

[1)] *Values calculated using the average hardness values determined for each component.*

The obtained results attest to the inclusion of the pipeline materials mechanical strengths in the requirements of ASME SA-335 for the prescribed steel grade P11 .

2.3. Analysis of the welded joint between DN50 / DN100 reducer and DN100 pipe elbow

Macroscopic analysis. The aspect of the welded joint near the area where the porosity appeared is shown in Fig. 6.

a) b) b) c)

Fig. 6. The macroscopic aspect of the eccentric reducer DN50 / DN100 welded joint with the pipe elbow DN100 in the porosity zone. a) joint overview after sectioning; b) detail of the joint surface in the porosity zone; c) section in the pipe wall at 30 mm distance from the porosity; d) section in the pipe wall where the porosity is located.

The images show that the wall thicknesses are significantly smaller in the welded joint zone, when compared to those at distances of more than 10 mm from the joint. One may also note that the penetration of the wall took place in the welded seam.

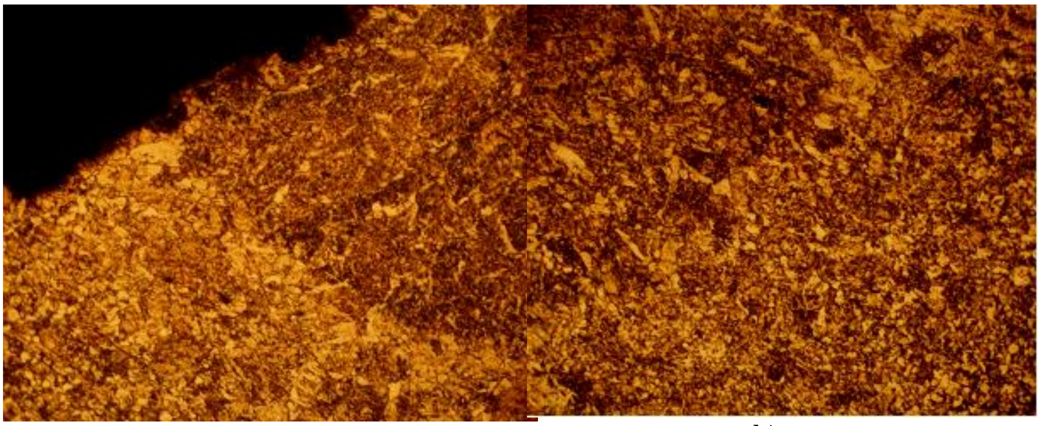
After dimensional examination, the welded joint between the DN50 / DN100 eccentric reducer and the DN100 pipe elbow revealed some characteristics, namely:

- on the outer surface of the joint, the edges of the reducer and pipe elbow appear curved inwards, an unfavorable situation for the stress level of the joint;
- the width of the welded seam is large, with values up to 19 mm on the joint circumference, namely up to 2.4 times greater than the nominal wall thickness;
- the height of the welded seam is approximately 4 mm as compared to maximum 2.2 mm for the intermediate acceptance level corresponding to the base material thickness of 8 mm [5].

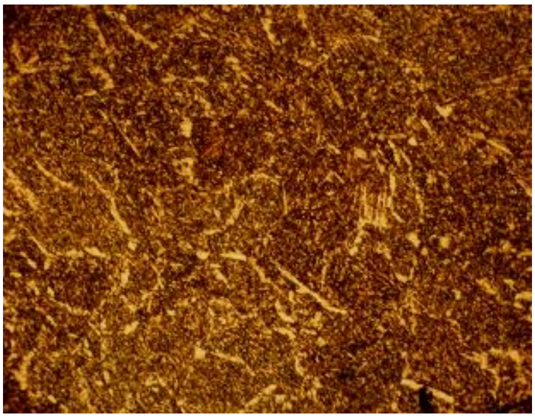
These aspects reinforce the previous paragraph observations with reference to probable deviations in shape and size in the execution of the DN50 / DN100 eccentric reducer and its joining with the DN100 pipe elbow.

Microstructure

Optical microscopy examination of the welded joint was performed in cross sections, placed at the limit of the position where the porosity was identified. Fig. 7 shows micrographs of the heat - affected zones of the DN50 / DN100 eccentric reducer, respectively of the DN100 pipe elbow, as well as of the welded seam [2].



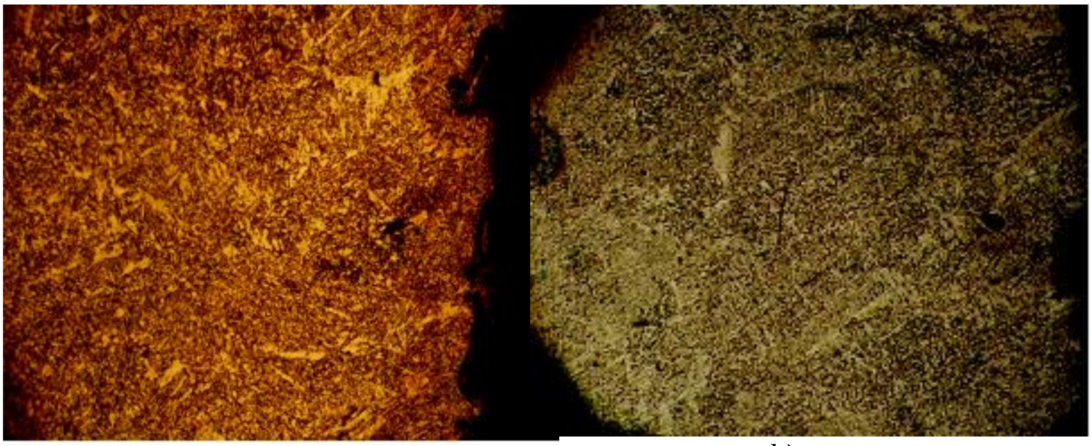
a) *b)*



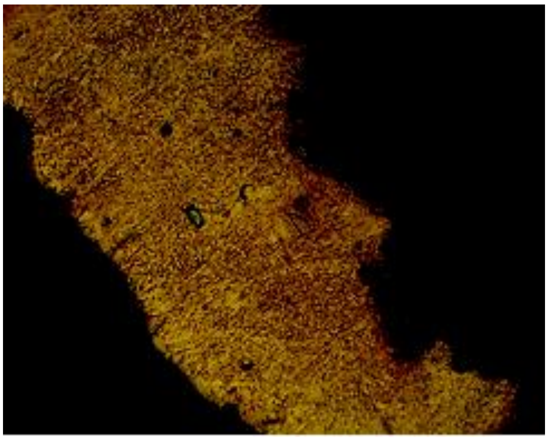
c)

Fig. 7. Microstructure of the eccentric reducer DN50 / DN100 with pipe elbow DN100 welded joint, in sections near the porosity (Nital etching, × 100); a) heat - affected zone towards the DN50 / DN100 reducer, mixed structure formed by bainite, fine pearlite and ferrite; b) heat - affected zone towards the DN100 pipe elbow, mixed structure formed by bainite, fine pearlite and ferrite; c) welded seam, structure formed by networks of ferrite, fine pearlite and traces of bainite. The structure preserves the disturbed character of a non-homogeneous, dendritic austenite from whence it derives.

The aspect of the welded seam in the penetration area of the metallic wall is presented in Fig. 8.



a) *b)*



c)

Fig. 8. Microstructure of the welded joint at the porosity boundary (Nital etching, × 100); a) traces of the welded seam at the joint boundary with the DN50 / DN100 reducer; b) welded seam thinned (damaged) by corrosion; c) continuation of the welded seam thinned (damaged) strongly by corrosion until piercing.

One may observe that the failure resulted from the metallic wall advanced degradation by general and pitting corrosion. No structural effects have been reported to justify any other type of failure in operation than those specific to corrosion [2].

Hardness. The hardness measurements were performed in a cross section of the welded joint between the DN50 / DN100 reducer and the DN100 pipe elbow, at a short distance from the porosity location. The results obtained are given in Table 5.

Table 5

Results of hardness measurements in the welded joint between DN50 / DN100 reducer and DN100 pipe elbow

No.	Position in the Joint	Vickers Hardness, HV10	
		Individual Values	Average Values
1	Reducer Base Metal	177 ; 172 ; 175	174.7
2	Reducer Heat - Affected Zone	180 ; 178 ; 175	177.7
3	Welded Seam	185 ; 180 ; 183	182.7
4	Pipe Elbow Heat - Affected Zone	190 ; 188 ; 183	187.0
5	Pipe Elbow Base Metal	148 ; 147 ; 145	146.7

One may see that the hardness values are within the normal values interval for the analysed steel grade, both as characteristic values of each examined area and as maximum differences between the base metal and the heat - affected zone or welded seam areas.

2.4. Analysis of products samples extracted from the inside of the pipeline

2.4.1 X-ray fluorescence analysis

The macroscopic aspect of the products extracted from the pipeline inner zone is shown in Fig. 9.


a)


b)

Fig. 9. Macroscopic aspect of deposit samples extracted from inside the pipeline; a) the reddish coloured sample taken from the DN100 / DN150 reducer area; b) the dark coloured sample taken from the DN100 pipe elbow area.

The results of X-ray fluorescence analyses are given in Table 6, in which the sulphur and chlorine contents are to be noted.

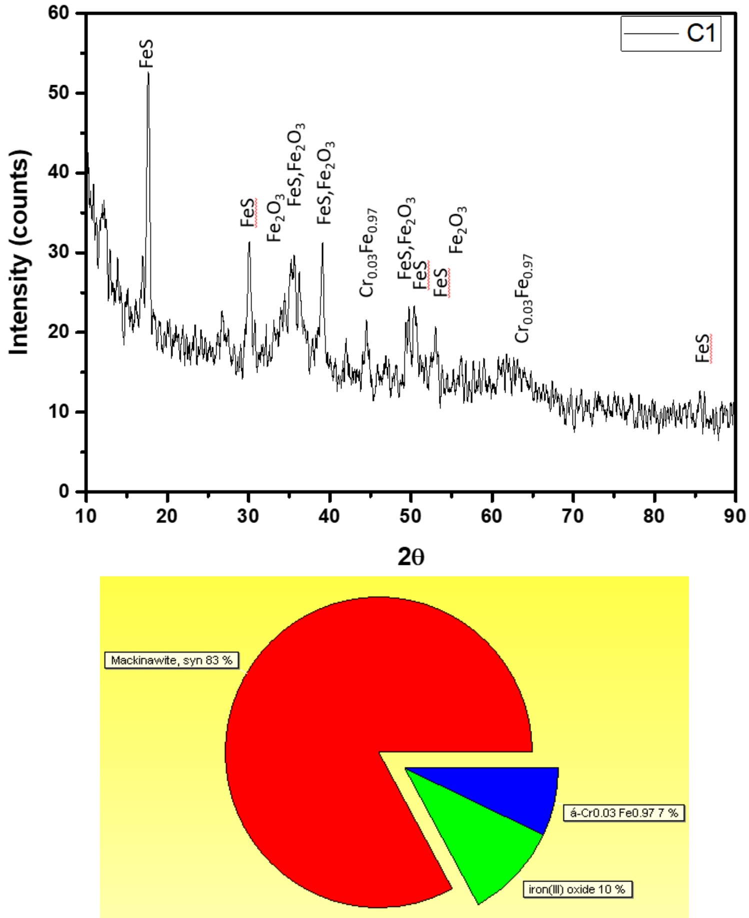
Table 6

Chemical elements present in the deposit samples taken inside the GH-120-201 pipeline, identified by the X-ray fluorescence technique

No. crt.	Chemical Element	Content, weight %	
		Reddish Deposit	Dark Coloured Deposit
1	Fe	58.58	56.84
2	S	9.71	24.25
3	Cr	9.00	0.84
4	Mo	1.24	0.35
5	Cl	1.22	0.41
6	Si	0.82	0.26
7	Al	0.31	0.11
8	Mn	0.20	0.10
9	Ni	0.19	0.10
10	Cu	0.11	0.17
11	Ca	0.08	0.04
12	W	0.08	0.09
13	Rh	0.02	-
14	As	0.01	71 ppm
15	V	0.01	-
16	Co	-	0.07
17	Zn	80 ppm	-

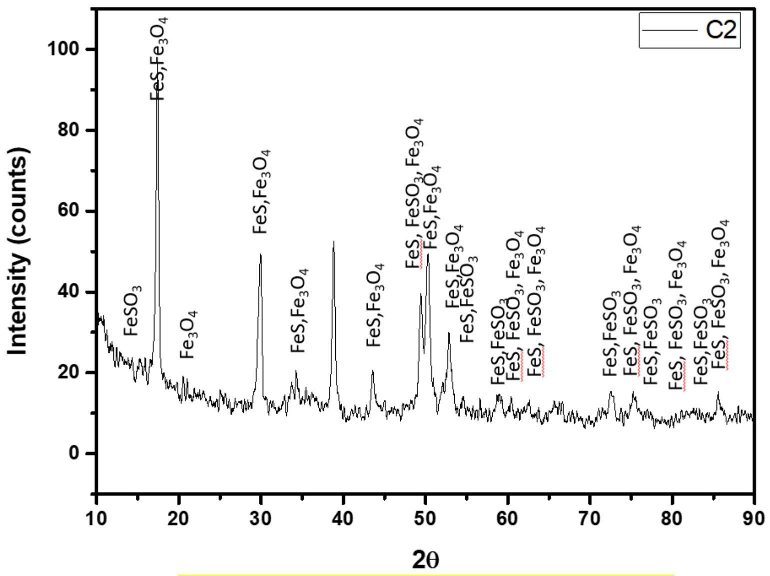
2.4.2. X-ray diffractometry analysis

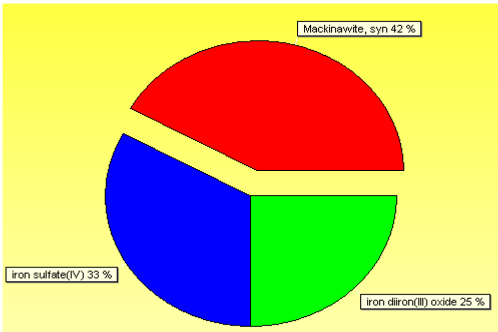
The results of the two deposit samples analyses are shown in Figs. 10 and 11.



No.	Visible	Ref. Code	Compound N…	Chemical Formula	Score	Scale …	SemiQua
1	☐	01-086-0389	Mackinawite,…	Fe S	28	0.835	83
2	☐	03-065-4607	á-Cr0.03 Fe0…	Cr0.03 Fe0.97	9	0.162	7
3	☐	01-089-0597	iron(III) oxide	Fe2 O3	0	0.063	10

Fig. 10. X-ray diffraction analysis of the reddish compounds sample taken from the DN100 / DN150 reducer zone.





No.	Visible	Ref. Code	Compound N...	Chemical Formula	Score	Scale ...	SemiQua
1	☐	01-089-2738	Mackinawite,...	Fe S	60	0.875	42
2	☐	01-071-2014	iron sulfate(IV)	Fe S O3	3	0.171	33
3	☐	01-079-0416	iron diiron(III)	Fe3 O4	4	0.371	25

Fig. 11. X-ray diffraction analysis of the dark coloured compounds sample taken from the DN100 pipe elbow zone

The results are semi-quantitative and refer to weight proportions. Given the predominance of iron compounds in the analysed samples, the sensitivity of the analyzes decreases, in which case the compounds present in proportions of less than 3% from the total may not be identified.

It is observed that, in addition to iron sulphide, both samples contain in various forms iron oxides, an aspect which indicates the presence of water in the hydrogen-rich gases of the recirculation system.

3. Assessment on the nature of corrosion processes that affected the analyzed pipeline

In refineries and the petrochemical industry corrosion processes that occur at operating temperatures of up to 260°C are considered to be low temperature corrosion. Widely used steels (non-alloy and low-alloy steels) are susceptible to low temperature corrosion but are not distincly dealt depending on the alloying degree or strength class [6].

In the low temperatures field the presence of Cr contents below 2% and Mo contents below 1% in steels have no significant effects on the general corrosion processes evolution in hydrocarbon media or hydrogen rich gases [3]. Consequently, the use of P11-type Cr-Mo alloy steel in the ascending branch of the pipeline, as against the non-alloy steel provided in the descending branch, was not able to bring the desired improvements in terms of service life.

3.1. Quality in manufacturing. The performed analyses revealed manufacturing deviations in relation to the technical documentation. The following issues were noted:

- differences in chemical composition of the pipeline steels as against the requirements of P11 steel grade according to SA-335;

- manufacturing the DN50 / DN100 reducer with an unusual geometry, by hot deformation with variable wall thickness and geometric deviations in the execution of the welded joint between the reducer and the DN100 pipe elbow.

The above mentioned deviations cannot be considered as cause of the pipe failure, but only as possible favouring factors in terms of failure location in the weld and possibly reducing the pipeline lifespan, when initial wall thickness deviations are present in thezone of the further appeared porosity.

3.2. Inorganic compounds deposited along the technological process

The analyses performed on deposit samples extracted from the pipeline ascending branch inner walls identified the sulphur and chlorine compounds presence. If the presence of H_2S was known from the composition of recirculated hydrogen analyses (see Table 7), that of chlorine compounds is new information concerning another source of corrosion processes .

In the inner pipe medium the presence of water cannot be ignored. It acts as a residue in the technological fluid or may result from condensation subsequent to aeration or washing actions, activating the corrosion process. The existence of water on the pipeline inner wall is proved by the products reddish color observed inside the pipeline and by results of their crystallographic analysis, obtained by diffractometric means.

Table 7

Composition of recirculated hydrogen through damaged pipeline

Compound	Unit	Value
H_2	vol%	88.02
Cl	vol%	5.49
CH*	vol%	5.259
O_2	vol%	0.12
N_2	vol%	0.36
CO	vol%	0
CO_2	vol%	0
H_2S	vol%	0.17
H_2S	g/Nm^3	2.661

*CH as hydrocarbons

3.3. The nature of the corrosion processes that could affect the pipeline ascending branch

The measured wall thicknesses showed average losses of wall thickness of up to 4… 5 mm, respectively corrosion rates of approximately 1 mm / year.

The only degradation process that can be considered is the pipeline inner wall corrosion, generated by the interaction of the technological medium with the metalllic part. The essential factors that generated and maintained the intense corrosion processes were sulphur and chlorine compounds in the presence of water.

Hydrogen sulfide dissolved in water is a weak acid and is corrosive because it is a source of hydrogen ions. Depending on the pressure, the pH acidity reaches 4 ... 3 values.

Hydrochloric acid and chlorine salts are important contaminants in the range of temperatures below the dew point. Through their ability to penetrate the metal protective layer, to increase the electrolyte conductivity and to interact with the metal, they are able to accelerate the corrosion processes. Corrosion rates increase with the decrease of the pH index, especially in the substrates of the deposits present locally on the technological flow path.

Synergistic effects of polysulfide - type sulphur compounds in the presence of minimum concentrations of chlorine compounds are reported in the literature as "barnacle-type corrosion" [6]. The risks of this type of corrosion are important in more severe working conditions than the present case (temperatures above 150°C and H_2S pressures above 100 bar).

In addition to the general and pitting corrosion processes discussed above, the wet medium present in the areas of the welded joints could generate a localized corrosion [8]. Such processes develop due to the different potentials generated by the differences in chemical composition and microstructure between the base metal and the welded metal. Other studies indicate numerous cases of cracking processes or thickness loss until the metallic wall is penetrated, generated from the inner zones of the pipes or pressure vessels welded joints [3, 7]. Table 8 shows the corrosion rates found in galvanic torques formed in welded joints of ASTM A-285, Gr. C non-alloy steel welded with different types of electrodes.

Table 8

Corrosion rates of galvanic torques between ASTM A285, gr. C steel and seams welded with different electrodes, in washing water at 90°C [6].

No.	Galvanic Torque	Corrosion rate, mm/y
1	Base Metal	0.69
	E7010-A1	0.81
2	Base Metal	0.46
	E7016	0.84
3	Base Metal	1.3
	E7018	1.2

One may observe that corrosion rates can reach considerable values.

4. Conclusions

1. The components of the pipeline ascending branch, respectively DN50 pipe, DN50 / DN100 reducer, DN100 pipe elbow and DN100 / DN150 reducer, were made of a Cr-Mo low-alloy steel which did not comply with the requirements of ASME SA-335 for P11 steel grade, as a result of deviations in Cr, Mo and S contents.

If only Cr contents are taken into account, the materials could assort with the requirements of ASME SA-335 for the P2 steel grade, which indicate 0.50…0.81% Cr. However, even in this case, the materials of the four components do not comply with requirements of ASME SA-335 concerning the Mo content, located at or below the lower limit for this grade, of 0.44% and the S content which, for three of the four components is significantly higher than the upper accepted limit.

2. The pipeline ascending branch failure was due to general and pitting corrosion processes, associated with galvanic corrosion in the welded joint zones. These corrosion processes were generated and maintained by the presence of sulfur and chlorine compounds together with water in the technological fluid. The processes aggressive character, characterized by corrosion rates of approximately 1 mm/year, was favored by the pipeline specific processing conditions and its geometry. Although they cannot be retained as failure cause, other favouring factors may have resulted from deviations in the manufacture of the DN50 / DN100 reducer and its welded joint with the DN50 pipe elbow.

3. It is recommended to revise the execution design for the DN50 / DN100 and DN100 / DN150 reducers, to re - manufacture the entire pipeline ascending branch as a spare part, paying attention to a careful execution, applying the appropriate heat treatments for all hot formed parts, including the post - welding heat treatment, which is to be applied only once, after making all of the welded joints.

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