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Investigation of Reasons for Damage to a Steel Pipeline Used For the Injection of Formation Waters

Abstract: The article presents results of test concerning reasons for the failure of a steel pipeline (DN 80) used for the injection of formation waters. The tests revealed that the perforation and subsequent material losses in the wall of the DN 80 pipeline made of steel L360NB were caused by deposit corrosion.

Keywords: deposit corrosion, pipeline damage, low-carbon steel

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Introduction

The exploitation of oil and natural gas deposits leads to the formation of a by-product, i.e. strongly mineralised formation waters separated (on the surface) from extracted hydrocarbons. One of the most effective methods of the disposal of such waters is their injection into deep geological structures satisfying specific requirements. Formation waters are highly mineralised. Contents of chemical compounds dissolved in such waters are restricted within wide ranges. The chemical nature of formation waters depends on collector characteristics and often changes with time. In terms of their chemical composition, formation waters are usually highly mineralised chloride-sodium brines. In addition to ions of sodium, potassium, magnesium, calcium as well as chloride, sulphate and carbonate ions, formation waters usually contain traces of radium, strontium, copper, bromine, iodine, manganese, iron, mercury and lead ions. Formation waters also contain deliberately added pollutants, i.e. chemicals facilitating exploitation including methanol, glycols,

detergents, corrosion inhibitors, paraffin release inhibitors etc. The pollution of formation waters is also affected by components of oil or gasoline condensates present in the form of emulsion or layer on the water surface or adsorbed on the surface of deposits and slurries contained in formation waters. Formation waters are usually transported by means of systems of pipelines which should be made of materials resistant to the effect of injected medium [1–3].

Subject and objective of tests

The tests discussed in the article involved a fragment of a pre-insulated steel pipeline used for the injection of waste materials. The diameter of the pipeline made of steel L360NB (PN-EN 10208-2:2011[4]) (Fig. 1a) amounted to 80 mm. The operation of the pipeline was accompanied by leakage. Preliminary visual inspection following the removal of the insulation revealed the presence of damage located in the pipe material (Fig. 1b). The tests aimed to identify reasons for the above-named leaks in the pipeline.

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Visual tests

The visual tests concerning the pipeline fragment revealed the presence of a hole having a diameter of approximately 9.0 mm. The edges of the damaged area were irregular. The performance of the visual tests of the internal surface of the pipe required cutting out the damaged area along the dashed line marked in Figure 2a.

The internal walls of the pipe contained rusty deposits (Fig. 2b, 3a), under which pipe material losses were detected. An exemplary pipe material loss is presented in Figure 3b.

Chemical composition analysis

The analysis of the chemical composition involved a fragment of the pipeline after the previous cleaning of its surface. Percentage contents of chemical elements were identified using a spark emission spectrometer. The chemical analysis results are presented in Table 1. In addition, Table 1 presents the chemical composition of steel L360NB in accordance with the requirements of the PN-EN 10208-2:2011 [4] standard.

The chemical composition analysis result revealed that the chemical composition of the base material of the test specimens was



Fig. 1. Fragment of the pipeline (DN 80) (a), visible damage to the pipe wall (b)



Fig. 2. Damage to the pipeline (DN 80), external pipe surface (a), internal pipe surface (b)

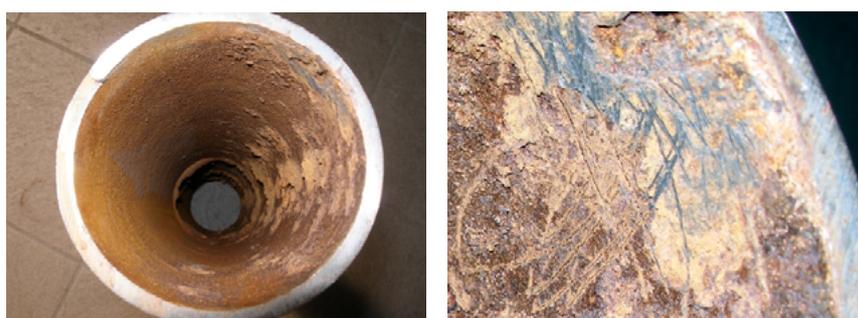


Fig. 3. Main view of the internal surface of the pipeline (DN 80) (a), fragment of the surface with the visible material loss (b)

Table 1. Results of the chemical composition analysis concerning the specimen sampled from the pipeline (% by weight)

Element	C	Mn	Si	P	S	Cr	Ni	Mo	Cu	Al	V	Ti
L360NB	0.13	1.02	0.20	0.016	0.007	0.05	0.04	0.01	0.07	0.028	0.003	0.003
Required for L360NB*	≤0.2	≤1.6	≤0.45	≤0.025	≤0.02	≤0.3	≤0.3	≤0.1	≤0.25	0.015–0.06	≤0.1	≤0.4

* Chemical composition of steel L360NB in accordance with the requirements of the EN 10208-2:2011 standard

Table 2. Static tensile test results

Specimen	R_e , MPa	R_m , MPa	A_5 , %
R1	419.2	580	26.7
R2	433.1	589.6	28.0
Requirement for L360NB*	min. 360	min. 460	min. 22

* Mechanical properties of steel L360NB in accordance with the requirements of the EN 10208-2:2011 standard

consistent with the requirements of the PN-EN 10208-2:2011 standard in relation to steel grade L360NB.

Tests of mechanical properties

The static tensile test of the base material was performed in accordance with the requirements contained in the PN-EN ISO 6892-1:2016-09 [5] standard, using a testing machine equipped with a computer-aided system enabling the control of the process and the recording of test results. Tests concerning the mechanical, i.e. tensile strength R_m , yield point R_e and plastic properties of the material, i.e. elongation A_5 were determined using flat specimens made in accordance with the recommendations specified in the PN-EN ISO 6892-1:2016-09 standard. The flat specimens were sampled along the longitudinal axis of the test pipe. The tests were performed at a room temperature of +22°C. The test results concerning the material specimens are presented in Table 2.

The results of the mechanical tests involving the material specimens sampled from the pipeline revealed that the test steel satisfied the requirements of the PN-EN 10208-2:2011 standard in relation to steel grade L360NB.

Macro and microscopic metallographic tests

Table 3 contains macroscopic photographs presenting the cross-section of the pipe in the area of material losses. The macrostructure of the specimens was revealed using Adler's reagent. Table 3 also presents the microstructure of the base material of specimen no. 1 and the

microscopic image near the outer and inner surface of the pipe. The microstructure of the specimens was revealed using Nital.

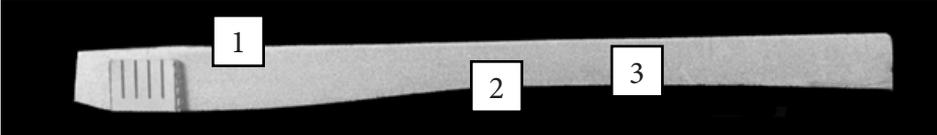
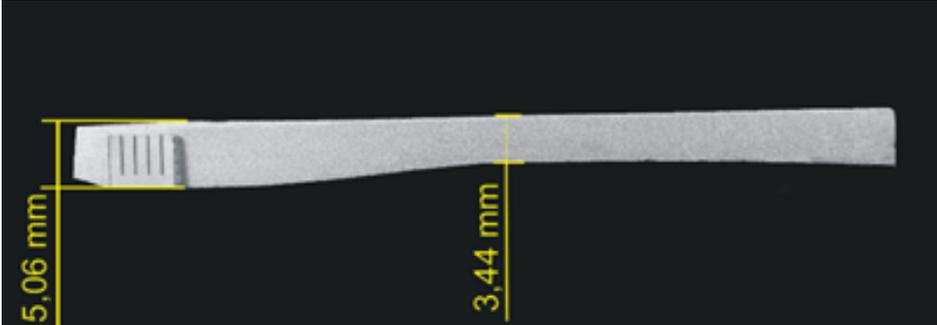
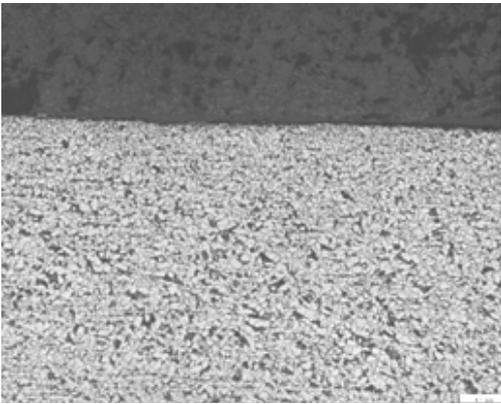
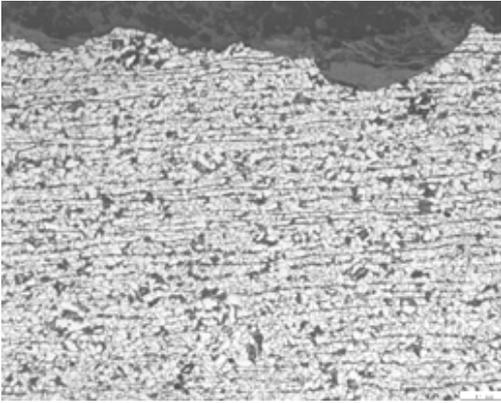
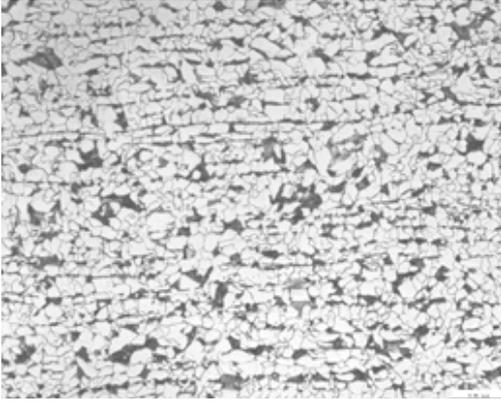
The macroscopic metallographic tests of specimen no. 1 revealed the reduction of the pipe wall thickness. In specimen no. 1, the percentage material loss in relation to a nominal wall thickness of 5 mm amounted to 31.2%. The microscopic metallographic tests of specimen no.1 revealed significant surface irregularities inside the pipe. The microscopic structure of the base material of specimen no. 1 was proper and did not differ from the structure typical of this material group.

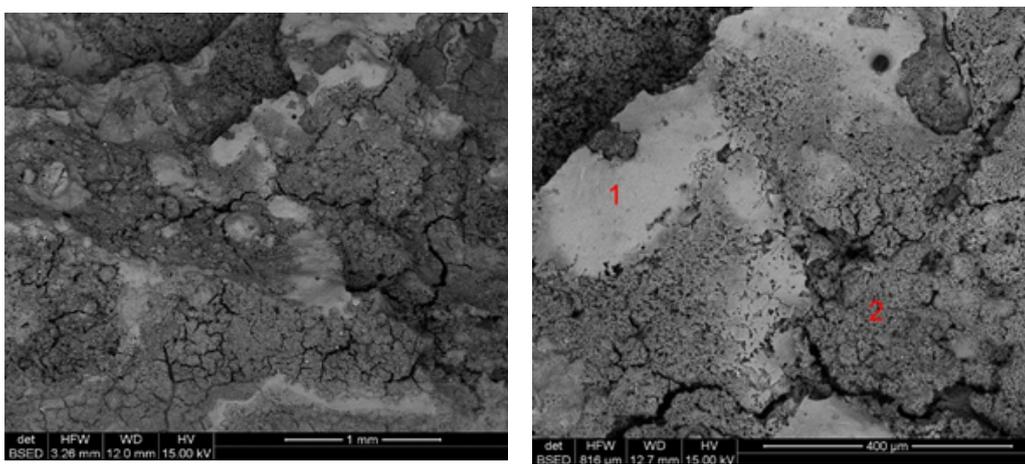
Macroscopic tests (SEM) of the deposits

The material used in the tests was a fragment of the pipe containing perforation (see Fig. 2). The tests of the deposits present on the internal surface of the pipe and in the cross-section of the pipe were performed using an Inspect F scanning electron microscope equipped with an EDS detector enabling the analysis of chemical composition in micro-areas.

Figures 4 through 6 contain test results concerning the deposits next to the perforation on the internal surface of the pipe. The deposits present on the pipe surface differed both in terms of morphology and chemical composition. The deposits were dominated by iron, oxygen, sulphur and chlorine. The deposits characterised by the expanded surface also contained the significant amount of silicon as well as aluminium, sodium, magnesium, potassium and calcium (Fig. 4 and 5). The area where the surface layer had fallen off the pipe was

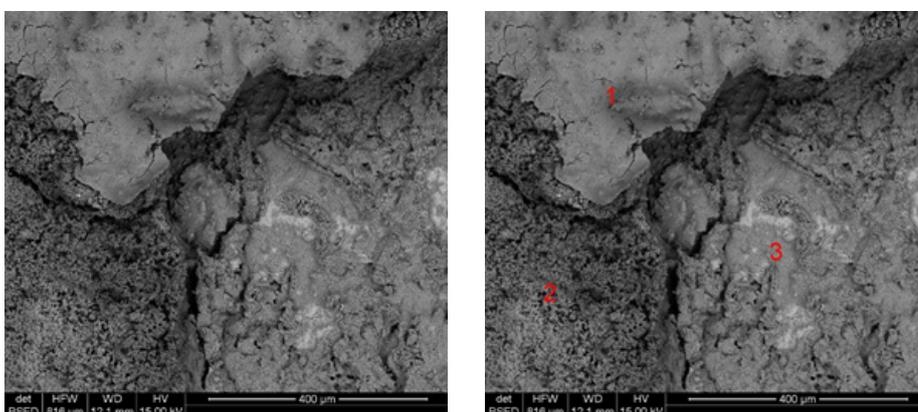
Table 3. Microscopic metallographic test results – specimen no. 1

Microscopic image	Description
Areas of microscopic photographs – specimen no. 1	
	
	
<p style="text-align: center;">1</p>	<div style="text-align: center;">  <p>Etchant: Nital; mag. 100x</p> </div> <p style="text-align: center;">External surface of the pipe ferrite + small amounts of banded pearlite</p>
<p style="text-align: center;">2</p>	<div style="text-align: center;">  <p>Etchant: Nital; mag. 100x</p> </div> <p style="text-align: center;">Internal surface of the pipe ferrite + small amounts of banded pearlite Note: visible corrosion on the pipe surface</p>
<p style="text-align: center;">3</p>	<div style="text-align: center;">  <p>Etchant: Nital; mag. 200x</p> </div> <p style="text-align: center;">Base material (MR) ferrite + small amounts of banded pearlite</p>



Elements, %	1	2
O	39.5	36.0
Na	-	0.6
Mg	-	0.5
Al	-	2.5
Si	0.5	8.4
S	2.1	2.5
Cl	3.7	3.9
K	-	0.8
Ca	-	0.4
Mn	0.4	0.3
Fe	53.8	44.2

Fig. 4. Results concerning the identification of the deposits on the internal surface of the pipe, around perforation



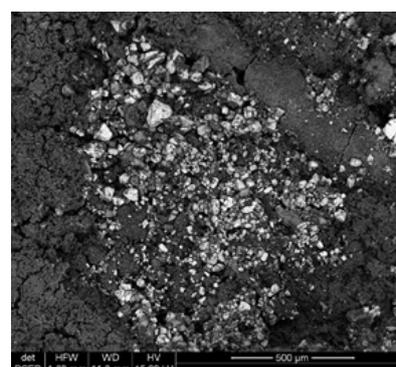
Elements, %	1	2	3
O	28.8	19.6	22.6
Na	0.7	0.7	0.8
Mg	0.3	0.3	0.2
Si	0.2	0.2	0.6
S	4.7	14.9	6.2
Cl	0.8	1.0	0.7
Ca	0.3	0.6	0.3
Mn	0.8	0.6	0.4
Fe	63.5	62.1	68.3

Fig. 5. Results concerning the identification of the deposits on the pipe surface

characterised by the high content of sulphur (Fig. 5). The deposit surfaces contained clusters including primarily oxygen, sulphur and barium (Fig. 6).

Figures 7 through 10 contain test results related to the deposits on the cross-sectional metallographic specimen. As a result of the preparation of the metallographic specimen, a significant amount of deposits, loosely connected with the base, fell off. The tests involved the layer adjacent to the pit surface (Fig. 7 and 8). The tests revealed that the dominant chemical elements present in the deposits on the surface were oxygen and iron. In addition, the deposit-related tests also revealed the presence of sulphur, restricted within the range of 0.7% to 35% (Fig. 9 and 10).

The deposits also contained silicon, chlorine and calcium (up to 1%). The deposits at the



Elements, %	
O	27.5
Na	1.0
Si	0.4
S	16.2
Ca	1.0
Ba	50.4
Fe	3.5

Fig. 6. Clusters of particles containing oxygen, sulphur and barium on the surface of the deposits

bottom of the pit contained a slight amount of sulphur and significant amounts of oxygen and iron. The deposits were locally characterised by the high content of carbon and chlorine (Fig. 9).

The layer of deposits contained bands characterised by the high content of carbon, significantly decreasing the continuity of the deposit later (Fig. 10).

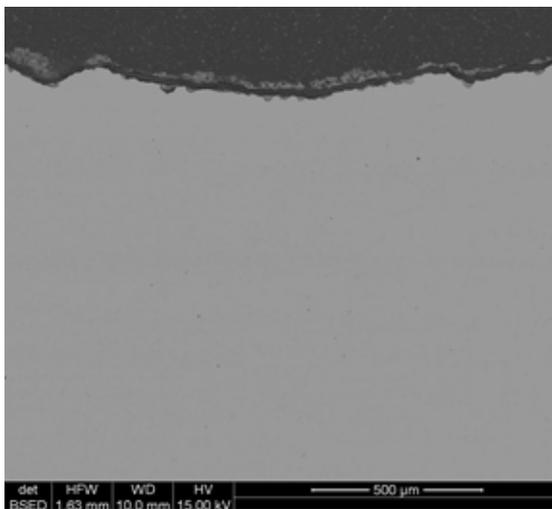


Fig. 7. Edge of the pit bottom outside perforation

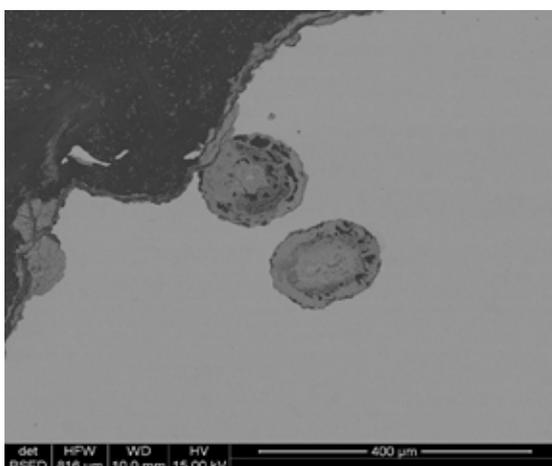


Fig. 8. Side edge – pits

Elements, %	1	2	3	4	5	6
C						16.6
O	28.4	29.7	30.6	7.4	30.0	29.4
Si	0.4	1.3	0.4	0.3	0.5	0.6
S	4.0	4.7	1.5	35.5	0.7	1.0
Cl	0.5	0.5	0.5	0.5	0.3	4.2
Ca	0.5	0.4	0.4	0.7	0.6	
Mn	0.6	0.7	0.5		0.6	
Fe	65.7	62.6	66.1	55.7	67.3	48.1

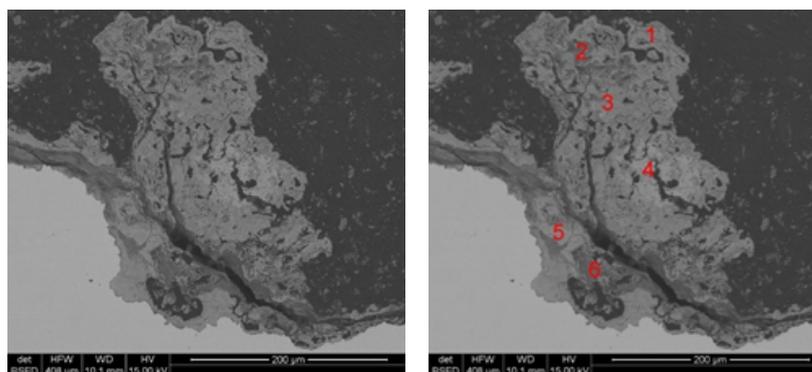


Fig. 9. Results concerning the identification of the deposits on the pit surface

Elements, %	1	2	3	4
C		6.9		
O	28.7	23.9	26.2	31.5
Si	0.4	0.7	0.3	0.9
S	1.5	2.0	1.1	1.6
Ca	0.9	1.0	0.6	0.8
Mn	0.8	0.5	0.6	0.7
Fe	68.1	65.1	71.3	64.5

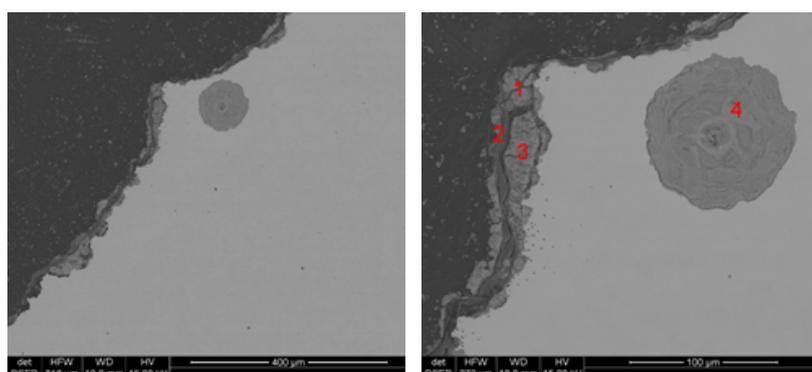


Fig. 10. Deposits on the pit surface

Test results – discussion

Visual tests revealed the presence of pipeline surface perforation having a diameter of approximately 9.0 mm (Fig. 2a). The visual tests of the internal surface of the pipeline revealed the presence of rusty deposits (Fig. 2b), under which it was possible to notice pipe material losses (3b).

The tests concerning the chemical composition as well as the mechanical tests of selected element confirmed the conformity of the materials with provided documentation. The results of the metallographic macroscopic tests of specimen no. 1 revealed the reduction of the pipe wall thickness. As regards specimen no. 1, the percentage material loss in relation to a nominal wall thickness of 5.0 mm amounted to 31.2%.

The metallographic macroscopic tests did not reveal any changes or material imperfections. The microscopic structure of the base material of specimen no. 1 was ferritic-pearlitic and did not differ from the structure typical of this material group.

The tests concerning the deposits present in the pipeline (DN 80), performed using a scanning electron microscope, revealed that the deposits present on the surface varied both in terms of morphology and chemical composition. The deposits were dominated by iron, oxygen, sulphur and chlorine. The deposits characterised by the expanded surface also contained the significant amount of silicon as well as aluminium, sodium, magnesium, potassium and calcium. The area where the surface layer had fallen off the pipe was characterised by the high content of sulphur. The deposit surfaces contained clusters including primarily oxygen, sulphur and barium.

Reasons for damage

The observations revealed that the reason for the perforation and subsequent material losses in the DN 80 pipeline wall made of steel L360NB was deposit corrosion. Deposit corrosion is present in areas containing deposits composed of products brought by water/solution (e.g. particulates present in water) or loose corrosion products. Galvanic concentration cells (differential aeration cells) are formed in the presence of the solution, at the interface between the base material and the deposit. The parts of the base surrounded by the solution characterised by the high concentration of oxygen constitute positive poles (cathodes), whereas the parts covered by deposits and surrounded by the solution characterised by the lower concentration of oxygen constitute negative poles (anodes). Corrosion damage affects the base area located under the corrosion deposits [6].

The deposits were characterised by high contents of sulphur and chlorine. Because of the fact that the pipeline was used for the transport of water it can be assumed that the dissolution of sulphates resulted in the formation of sulphuric acid. Present on the internal surface of the pipe, the acid concentrated under the surface of the deposits and reacted more intensively with the metal. By reacting with the pipe material, the sulphuric acid formed porous deposits,

thus increasing the area of its penetration into the pipe wall. The deposits also contained a layer characterised by a high carbon content, significantly decreasing the adhesion of corrosive deposits to the surface. Particulates (i.e. particles characterised by high contents of oxygen, sulphur and barium) present in the polluted water were responsible for the removal of the above-named deposits, intensifying the erosive and corrosive effect of water [7, 8].

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