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STRESS-CORROSION CRACKING (SCC) IN RUSSIAN GAS PIPELINES

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Abstract

The main origins of SCC failures in large diameter natural gas pipelines have been investigated. Laboratory techniques have been developed to simulate the corrosion process which have been used to establish mitigation measures and to develop procedures for repair and rehabilitation of existing trunk pipelines. The paper describes the current state of the art in managing the SCC problem in Russian gas pipelines.

Stress Corrosion Experience

Among the factors that caused failures in the main Russian gas pipelines in the past 10 years, a significant role was played by stress corrosion cracking (SCC).

The percentage of SCC failures in comparison with other causes is constantly growing and currently is about 50 percent (despite a general reduction of number of failures)

Failures caused by SCC of the pipe metal might be followed by pipeline breaks (Figure 1, below), gas losses and transportation interruption. This leads to huge losses for gas-transportation companies.

Considering the above evidence the main strategy for combating SCC for technicians, engineers and maintenance crew is searching for methods of early diagnosis, prophylactics and early inspection of gas pipelines that have been subjected to SCC, plus efforts eliminate reasons for SCC on newly built gas lines.

The strategy for struggling with SCC has three parts consists of researching SCC, developing tools for technical diagnosis and also tools for salvaging as well as methods for inspection of gas pipelines, prone to SCC, i.e.

- Researching of reasons for initiation and development processes of SCC.
- Development of tools for in-line inspection.
- Development of tools and methods for diagnosis and repairing of gas pipelines, subjected to SCC.

The parts of the Program are considered below.

Activities in the first part aim to establish the technical demands of the pipes and resistance, to SCC. At the same time it is necessary to establish the conditions of exposure and the stress-strain state of pipe leading to SCC damage of the metal.

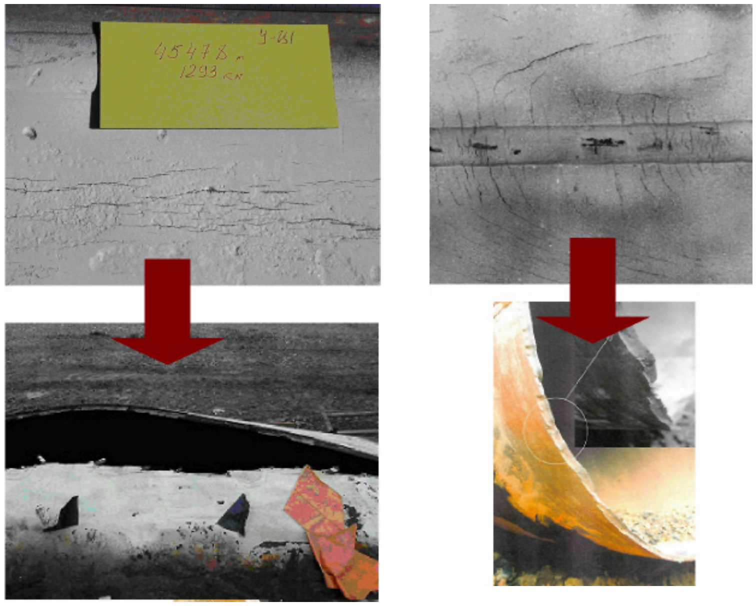

Figure 1. SCC damage of the pipe material

Based on the aims of the first part of the Program we have collected all knowledge about the research purpose.

SCC phenomena have been known for a long time. It appears in various metal and non-metallic materials. The most common signs of SCC are groups of parallel cracks, orthogonal to the main mechanical stresses which grow deeply perpendicular to the product's surface.

SCC appears to be a synergistic process involving a combination of the following reasons (Figure 2):

(a) Exceeding the limit of the threshold stress for the given material

(b) Existence of a certain environment that is specific for each material and which directly contacts the surface of the material and causes cracking for a given stress-strain state.

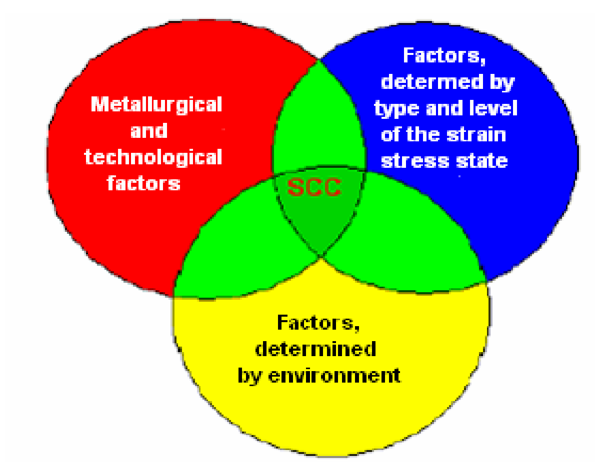

Figure 2. Groups of reasons for initiation and development of SCC

Some types of SCC depend on temperature (carbonate-bicarbonate steel cracking SCC of austenitic steels in chlorides environments, etc) or on air moisture ("seasonal" cracking of projectile cartridges during World War I).

There is an interesting natural phenomenon for SCC processes. Environments, active for SCC, are always passive for pitting and total corrosion for the same materials in the unstressed condition (i.e. chlorides for austenite stainless steels). This also applies to stress corrosion on Russian main gas pipelines:

- Groups of cracks, parallel to the pipe axis can be observed in gas lines, if the main stresses on this piece of pipeline are hoop exploitation stresses (Figure 1 top left) for longitudinal-welded pipes and in for spiral-seam thermally improved pipes. If longitudinal stresses are higher than the hoop stresses, as can be seen in the case of bending stresses, the cracking direction is perpendicular to the pipe axis, (Figure 1 top right).

- The mineralization of environments, contacting the steel are mainly the same as drinking water and they are not active for pitting and total corrosion (Figure 3).

Potential for SCC in Russian main gas pipelines usually involves:

(a) Diameter liable to SCCis mainly 1020, 1220, 1420 mm;

(b) Usage of cold coating for anti-corrosion protection of pipes;

(c) A working pressure at compressor station exit points of 5.4 and 7.4 MPa;

(d) A hydrogen index for soil electrolytes in SCC areas between pH 5 to 7 (weak acidic or neutral environment).

Components, µg/g	Main linepipe 'Yamburg-Elets 1' (1.383 km)	Main linepipe 'Krasnodar region-Serpukhov city'	Main linepipe 'Punga-Ukhta-Gryazovets' (586 km)
Calcium	0,36	16,16	2,48
Magnesium	0,54	2,02	5,81
Fluorine	1,55	15,03	29,62
Chlorides	1,1	132,49	25,62
Sulfates	0,018	2,26	207,45
Phosphates (PO_4^{3-})	7,92	1,47	19,37
Iron (Fe^{3+})	8,45	7,1	8,3
Nitrates	0,48	23,9	18,4
Nitrites	0,53	0,32	0,73
Sulfides (S^{2}-)	9	less then 1,0	6,09
Sodium	0,49	808,1	29,87
Aluminium	0,074	no	1,04
Selenium (Se^{2+})	no	no	10,8
Lead (Pb^{2+})	No	no	4,97
Arsenic (As^{5+})	No	no	0,004
Silicic acid	413	no	4219
Formic acid	0,144	no	1,24
Lactic & Acetic	1,44	no	no

Failures caused by SSC (orange)

No failures caused by SSC (green)

Figure 3. Chemical composition of ground electrolytes, µg/g.

We should add that the pH value of the soils is similar to regions where SCC occurs in Canadian gas lines. And in US gas pipelines where SCC falures take place in soils with pH value greater than 12 (alkali environment)

The exact SCC mechanism at low pH values is not yet determined. Russian and Canadian scientists are performing active research on this problem. They rely on the following hypotheses in their research:

(a) Cracks appear and grow according to a mechanism of anodic dissolving of the steel.

(b) Cracks appear and grow according to the mechanism of strength reduction with adsorption (so called Rebinder effect)

(c) Cracks grow because of "hydrogen embrittlement" of the steel with hydrogen that develop as a result of electrolysis of the soil electrolyte at high potentials of electrochemical protection of pipe metal from corrosion.

The authors support the second mechanism, we believe that one or several component of the soil electrolyte that is surface active in reference to the pipe metal, including hydrogen, can cause strength reduction. Significant dissolution is not necessary, surface adsorption is enough to reduce strength.

An analysis of gathered information allowed development of correlations between project and construction parameters, gas pipelines exploitation regimes and conditions for SCC appearance.

Nowadays we can be sure in the following facts:

(a) Regimes of active electrochemical protection of gas pipelines do not influence appearance and development of SCC

(b) Values of potentials reached during electro-chemical protection of Russian gas lines do not cause metal saturation with hydrogen and hydrogen embrittlement, based on the observer plastic deformation at the tip of a stress corrosion crack (Figure 4).

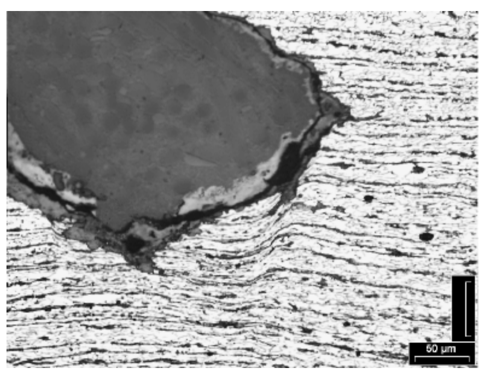

Figure 4. Plastic deformation on the top of SCC

We have observed that SCC in Russian gas lines appears at points where the following conditions are met:

(c) Anti-corrosion coatings in the form of short-term film had been used, and the effectiveness of such protection is lost after 5-10 years of exploitation, after which the metal begins to contact soil electrolyte directly.

(d) The construction team did not completely follow the construction design, or the design did not include local geo-technical peculiarities of the area (landslides, etc), possibly leading to a change of stress-strained state of the pipeline. For example, distribution of stresses in sections of pipe, such as bending because of landslides not considered during making gas line draft. Such stress-strained states of pipe can lead to destruction. (Figure 1 bottom right).

A long study of SCC problem in Russian gas lines shows that after degradation of coatings, when the electrolyte begins to contact the metal surface directly, metallurgical factors become dominating. From this moment, the following metallurgical parameters start to influence development of stress corrosion processes in large-diameter pipelines:

(a) Internal metal stresses, introduced during pipe making process
(b) SCC susceptibility, depending on the technology of thermo-mechanical processing of the steel.

These conclusions are based on results of tests, carried out by the method of stretching with at slow strain rates and contact of the sample with the active environment. Tests of pipe steel, made with of various technologies, were carried out on conventional cylindrical explosive samples with a speed of deformation equal to $5*10^{-7}$ sec^{-1}.

The parameter, showing the stability of steel to SCC, using the factor of preservation of plasticity Kψ (the degree of plasticity Zψ), computed from a ratio between the relative narrowing of the metal in air and in a special solution, causing SCC (ph=5,l)

$$K_\Psi = \frac{\Psi_K}{\Psi_0}; \qquad Z_\Psi = \frac{\Psi_0 - \Psi_K}{\Psi_0};$$

Ψ_0 - Relative narrowing of the sample in the outdoor test;

Ψ_K - Value in the test environment.

Table I shows the results of SCC stability of the steel (see the Table II) carried out on the basis of the method described above.

Table I - Results of SCC stability tests, carried out on the basis of the slow strain rate method.

no.	Steel grade	Pipe and plate/strip technology	Kψ	Zψ
1	X65	Longitudinal seam's pipe; TMCP+ACC steel	0,39	0,61
2	X70	Longitudinal seam's pipe; TMCP+ACC steel	0,38	0,62
3	10G2FB	Spiral pipe; bulk heat treatment (Q&T), *basic metal*	0,37	0,63
4	10G2FB	Spiral pipe; bulk heat treatment (Q&T), *weld joint*	0,37	0,63
5	10G2FB	Longitudinal seam's pipe; TMCP+ACC steel; pilot batch	0,43	0,57
6	X70 (Italy)	Longitudinal seam's pipe; TMCP steel; standard: TU14-3-995-81	0,24	0,76
7	09 G2FB	Longitudinal seam's pipe; TMCP steel; standard: TU14-3-741-78	0,30	0,70
8	17G1S	Longitudinal seam's pipe; Normalized steel; standard: TU14-3-109-73	0,23	0,77
9	X70 (Japan)	Longitudinal seam's pipe; TMCP steel; standard: TU14-3-995-81	0,24	0,76
10	14G2SFB	Longitudinal seam's pipe; TMCP steel; standard: TU14-3-446-72	0,30	0,70
11	17G1S-U	Longitudinal seam's pipe; TMCP steel	0,17	0,83

Considering the above, we can suggest, that the largest level of resistance to SCC involves pipes made of controlled rolled steel with the accelerated cooling or pipes after quenching and tempering. This can be explained by the high uniformity of the structure and fine grains of ferrite, which can be seen in the steel, (for pipes after bulk heat treatment - Q&T).

Table II - Chemical composition of pipe steel

Steel grade	C	Si	Mn	P	S	Cr	Mo	Al	V	Nb	Ti	N	Term of operation
17G1S	0,180	0,290	1,470	0,020	0,026	0,190	-	0,008	0,005	-	0,009	-	18
14G2SFB	0,170	0,450	1,650	0,015	-	0,100	0,050	0,020	0,100	0,035	-	-	18
14G2SAF	0,150	0,350	1,500	0,020	0,017	0,060	0,080	-	0,070	-	-	-	20
X70	0,092 0,097	0,180 0,280	1,800 1,600	0,027 0,018	0,005 0,003	0,050 0,030	0,020 0,020	0,020 0,050	0,010 0,040	0,040 0,040	0,020 0,020	-	10
X70	0,106 0,074 0,109 0.090 0,070	0,240 0,180 0,240 0,180 0,180	1,750 1,750 1,750 1,650 1,670	0,026 0,017 0,019 0,020 0,019	0,004 0,002 0,002 0,013 0,013	0,200 0,040 0,040 0,030 0,030	- - - - -	0,030 0,030 - - -	0,050 0,050 0,050 0,050 0,050	0,030 0,040 0,030 - -	- - - - -	0,010 0,013 0,009 0,008 0,008	11
X70	0,100	0,200	1,550	0,022	0,003	0,210	0,010	0,010	0,060	0,010	-	-	9
X70	0,120	0,280	1,590	0,018	-	0,300	-	-	0,070	-	-	0,020	14

The results should be considered as indicative of the tendency, because the applied strategy of the tests can not reproduce exactly both the real conditions of the biaxial stressed and deformed state of the actual pipe metal, which appears during usage of the pipeline, and also the composition of the actual ground electrolyte.

Chemical composition can not be considered as an independent maintenance factor for occurrence of SCC and must be taken into account in a aggregate with the production technology

In our opinion chemical composition of steels has a low influence on SCC. This can be seen in Table I where length of service of the gas line before appearance of dangerous stress corrosion cracks, and chemical composition, are not correlated.

JSC "Gazprom" conducts a complex program of SCC research, creating tools for technical diagnosis is of SCC, means for protecting gas pipelines and methods for repairing gas lines that suffer from stress corrosion cracking.

The program's goal is the solution of stress corrosion problem in Russian gas pipelines.

For detecting deterministic dependences between properties of pipe steel, details of near-pipe environment and the stress-strain state were made in 2005 year and the special strategy of accelerated tests of model full-sized samples of pipe steel were considered (Fig. 5).

The particularity of this strategy is that during the operation test metal is subjected to load which character is close to stress-strain state of applied gas pipeline. Real and simulated ground electrolytes are used as the conditions of environment.

Application of this strategy allows us to detect the main factors, which cause SCC in gas pipelines and to determine their critical parameter:

(i) The details of steel chemical composition and technologies of steel production, which determine steel SCC resistance.

(ii) Parameters of forming and welding of pipes, which determine the level and character of dispersion of remaining mechanical stresses in the pipe body;

(iii) threshold mechanical stress, below which SCC doesn't occur;

(iv) the parameters of soils and electrolytes, responsible for occurrence of SCC.

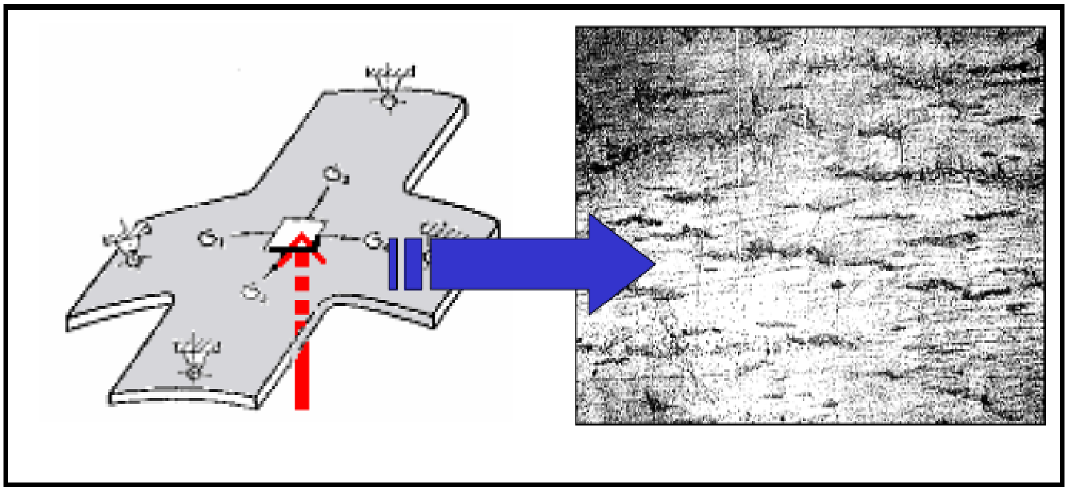

Figure 5. Strategy of firmness tests against SCC

This research will determine the level of requirements for plate steel, for forming and welding of pipes and to the surface strain, providing the resistance of pipes to SCC.

A practical solution to the SCC's problem has become possible at the expense of other development of measures, allowing us either to raise the stability to SCC, or to determine the pipe's remaining life in operation in conditions of SCC. These measures were developed during the realization of the second and the third part of program, aimed at developing means and methods of diagnosiss and repair of gas pipelines, subjected to SCC.

At present a number of measures have been worked out for detecting and efficient preventive repairing of SCC damage in Russian pipelines during their early and not such dangerous stages.

The most important result in this area is the creation and introduction in practice of equipment and technologies for in-line magnetic inspection, grounded on the principle of transverse magnetization. In Figures 6 and 7 examples are shown of intelligent pigs, intended for SCC's inspection of pipelines with diameter 1420 mm, and also the example of

For the successful diagnosis of damage caused by SCC, in-line inspection of pipelines should be used in combination with other designed and developing at present.

- strategy of detecting potentially dangerous areas in accordance with signs of crossing of the pipeline by the level of underground water (on the assumption of design, executive documentation and field researches);
- detecting of areas and sequence of in-line inspection;
- post-examination of the most dangerous defects;
- revision of the calculation of dangerous defects;
- determination of terms and methods of repairing;
- determination of terms of next in-line (priority) for inspection's undertaking.

From the results, received in the course of the diagnosis, an assessment of remaining safe operation life of pipeline is carried out using the designed strategy, and defined methods of repairing.

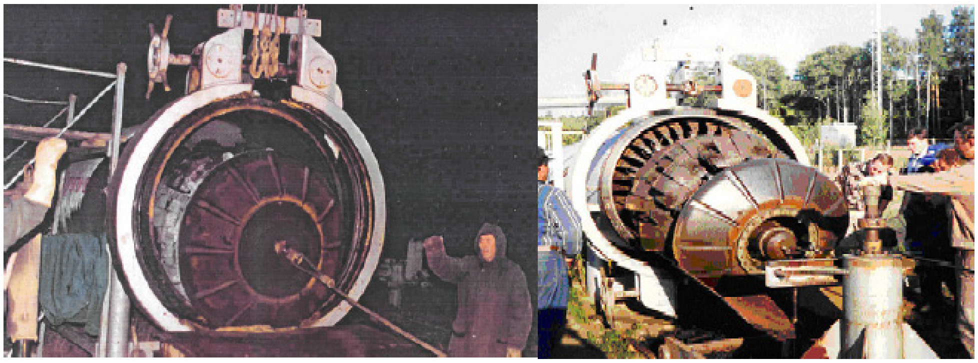

Figure 6 Means of inline inspection of pipelines

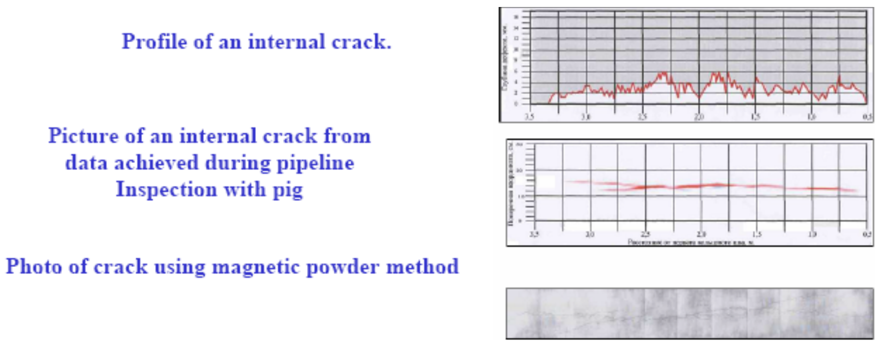

Figure 7. Pipe with internal crack

For the repair of pipelines subject to SCC a great variety of methods was developed, including:

(a) polishing of shallow cracks (Figure 8)

(b) reinforcement of defective areas by steel sleeve;

(c) welding of deep cracks.

External diameter of pipe mm	Maximum area of sample for welding, mm^2	Maximum length of sample for welding, mm	Maximum depth of sample for welding
1420	35000`	500	About 65% of thickness of pipe, but not lesser than 5 mm of remaining thickness of the pipe

Figure 8. Development of fitness criteria for repair and technology of SCC defects using repair welding

Conclusions

The described analysis of SCC in gas pipelines shows, that as a result of complex measures, introduced by JSC «Gazprom», preconditions have been established for development of pipes with increased level of stability to SCC and prolonged lifetime of gas pipelines, used in conditions of SCC.

The laboratory tests of linepipe reproduce almost real conditions of pipeline usage. The application of these tests allows us to determine critical factors, initiating SCC in linepipe steels.

The following methods were established:

- restablishment of reliability of pipes subjected to SCC;
- increase of stability level of pipes to prone to SCC;
- determination of remaining safe operation life of pipelines with SCC defects.