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Methodology for testing pipeline steels for resistance to grooving corrosion

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Abstract. The methodology for testing pipeline steels is suggested on the assumption that for the destruction of pipes in field oil pipelines by the mechanism of grooving corrosion the simultaneous fulfillment of such conditions as the occurrence of scratches on the lower generatrix of the pipe, eventually growing into a channel in the form of a groove, emulsion enrichment with oxygen, presence of pipe wall metal in a stressed state, presence of chlorine-ion in the oil-water emulsion is required. Tests are suggested to be carried out in 3 % aqueous solution of NaCl with continuous aeration by air on bent plates 150×15×3 mm, made of the analyzed steel, the middle part of which is under the action of residual stresses σ_{res}, close to the level of maximum equivalent stresses σ_{eqv} in the wall of the oil pipeline, with the presence of a cut on this part on the inner side of the plate as an initiator of additional mechanical stresses. Using the value of the modulus of normal elasticity of the analyzed steel, the degree of residual strain of the elastic-plastic body from this material, corresponding to the value $\sigma_{res} \approx \sigma_{eqv}$ is calculated, based on which the plates are bent to the required deflection angle, after which the cut is applied to them. After keeping the plates in the corrosive medium for each of them the increase in depth of the cut as a result of corrosion of the walls by the corrosive medium is analyzed, from which the rate of steel *K* by the mechanism of grooving corrosion is calculated taking into account the duration of tests. Corrosion rate values for two pipe steel grades determined by the suggested procedure are given. The comparison of *K* values obtained leads to the conclusion about the higher resistance to grooving corrosion of 09G2S steel.

***Key words*:** field oil pipelines; testing methodology; pipeline steels; resistance to grooving corrosion; corrosion rate; mechanochemical effect

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Introduction. Despite the intensive development of renewable energy sources [1], oil continues to be a major component of the overall global energy balance. Ensuring uninterrupted transport of oil and oil-containing products through trunk and field pipelines is an important scientific and technical challenge. Metal corrosion is the cause of accidents in many industries, including oil and gas industry. It has been estimated that in Russia there are over 80 000 pipeline [2] and reservoir [34] accidents annually, and the majority of them are due to corrosion-related damages [8]. The experience of operating field pipelines shows that the main cause of accidents is corrosion of the inner surface of the lower pipe generatrix, which occurs when pumping oil-water emulsions with heavy mineralized water containing solid abrasive particles through the pipeline [5]. This type of corrosion is referred to as grooving corrosion due to the specific appearance of the fracture site, resembling a stream flowing along the bottom of the pipe (Fig.1).

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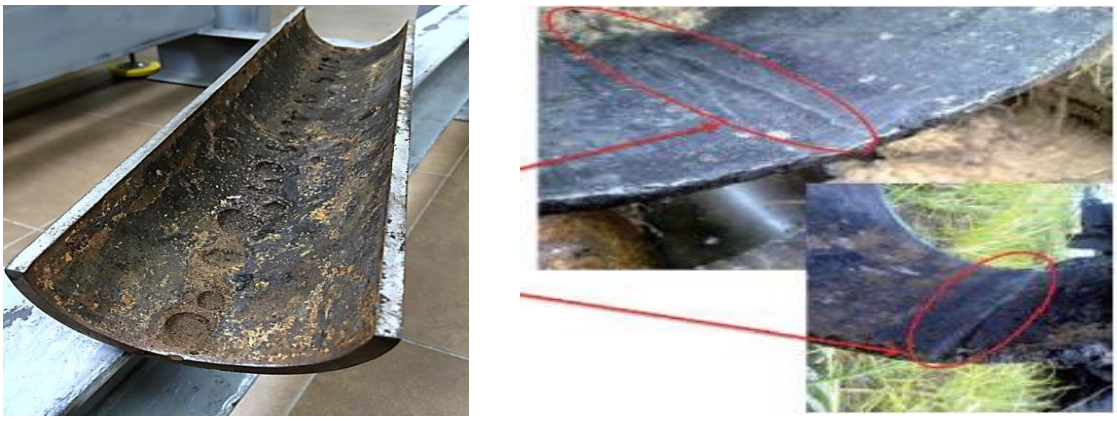


Fig.1. Typical view of a field pipeline affected by grooving corrosion

There are numerous papers on grooving corrosion, e.g. [4, 9, 14], but the mechanism of this process and factors influencing its intensity have not been finally determined. Particularly, it relates to the effect of pipeline stress state on the rate of corrosion damage of the pipe metal and the role of groove in the corrosion process [3, 25]. As the practice of field pipeline operation shows, though there are a number of developed protection methods (installation into the pipeline section of different devices that turbulate the emulsion flow [12], application of inhibitors [14], protective coating of the pipe inner surface [16], use of preliminary water discharge units, etc.) the problem of grooving corrosion in Russia and worldwide is still far from being completely solved. To the greatest extent, it is relevant for long-operating field pipelines, where sections of steel pipes damaged by grooving corrosion have to be periodically replaced with new ones that require replacement after some time.

This paper proposes the technique of corrosion laboratory testing of steels [11] under conditions simulating possible inter-field pipeline wall damage under grooving corrosion, which allows to select compositions that are resistant to grooving corrosion from existing and engineering pipeline steels and to further recommend these compositions for using in field pipelines. Another application of the technique is to study the effect of stressed state and the presence of a cut on the stressed structure, which simulates a trace of grooving corrosion, on the corrosion rate of the metallic structure in the reaction medium. The technique is not designed to determine resistance of pipeline steels in sulphur-containing media [24, 28, 32], as well as under conditions promoting stress-corrosion of steels [25, 30, 33] and stress corrosion cracking [22, 27, 29] due to significant differences in the mechanisms of these processes.

Statement of the problem. When developing the methodology, it was assumed that grooving corrosion of field pipelines occurs when the following basic conditions are simultaneously met:

• separation of the water-oil emulsion with the water fraction washing over the lower generatrix of the pipe;

• presence of dissolved oxygen in the water in contact with the metal at a sufficient concentration to allow the electrochemical corrosion reaction of the pipe metal with anodic control. (This may occur, for example, when oil-water emulsions are produced using formation water enriched with oxygen or when an oil-water emulsion is intensively mixed in contact with air). Only under this condition the level of pipe stress can affect the rate of metal corrosion;

• presence of corrosion active impurities in water of oil-water emulsions, coming from formation water, the most reactive of which is chlorine-ion [13] (influence of anion S^{2-} anion is not taken into account in this methodology), and highly abrasive solid particles;

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• effect of tensile stress on the pipe wall, facilitating the release of iron ions from the steel into the aqueous solution during the anodic phase of the process and, consequently, intensifying the corrosion process of the pipe metal;

• appearance of scratches on the lower generatrix of the pipe as a result of abrasion by solids contained in the emulsion, developing over time into a groove, the metal of the walls and bottom of which is subject to additional tensile stresses, maximum in the metal of the bottom part [4, 14, 26].

Methodology. In order to satisfy mentioned conditions, it is proposed to test steels for resistance to grooving corrosion in oxygenated aqueous chloride medium, on the samples subjected to tensile stresses close to the level of equivalent stresses in the pipe, with a grooving cut on them according to the following methodology.

Preparation for the tests. The value of maximum equivalent stresses arising in the pipe wall of the analyzed field pipeline during oil-water emulsion pumping is estimated, taking into account the presence of upward and downward sections on it, which cause bending of the pipeline [10, 23]:

$$\sigma_{eqv} = \sqrt{(\sigma_1 + \sigma_3)^2 - (\sigma_1 + \sigma_3)\sigma_2 + \sigma_2^2},$$

where σ_1 – ring stresses caused by internal medium pressure, MPa; σ_2 – longitudinal stresses caused by bends in the pipeline, MPa; σ_3 – stresses of technological origin remaining in the wall after pipe manufacture, MPa [6, 19].

For the 219×8 mm ascending pipeline section with a bend radius of 219 m, as one of the main ones in the nomenclature of field pipelines, at operating pressure of 4 MPa and temperature of pumped emulsion of 60 °C values σ_1 , σ_2 , σ_3 are 51, 95 and 35 MPa, parameter σ_{eqv} has a value ~ 160 MPa, which was used in calculations.

Plates of 150×15×3 mm in size are cut across the rolling direction (pipe axis) from rolled pipeline steels used for manufacturing welded pipes of field pipeline, or from the pipe body, in the case of pipes obtained by rolling. The plates are bent in clamps up to residual deflection, providing residual stresses σ_{res} in the middle, plastically deformed arc-shaped part of plates, close to σ_{eqv} in a pipe. Thus, as proved in [35], on the inner side of the plates these are tensile residual stresses, and on the outer side – compression stresses. Provision of equality $\sigma_{res} = \sigma_{eqv}$ is reached by providing the metal in the middle part of the plate necessary degree of residual deformation ε_{res}, which according to Genki theorem [18] (Fig.2) for elastic-plastic body corresponds to the value σ_{res}:

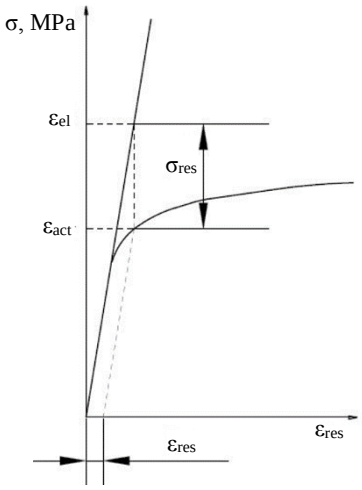


Fig.2. Graphical interpretation of the solution to the problem of finding residual stress in an elastic-plastic body

σ_{el} – stress that would be created in the body, assuming the ideal elasticity of its material; σ_{act} – is the actual stress, corresponding to a given value of the residual strain on the tensile diagram of the material

$$\varepsilon_{res} = \sigma_{res}/E, \quad (1)$$

where E – modulus of normal elasticity for the steel analyzed.

Considering that for all pipeline steels the E value does not differ significantly (200 GPa), the required level of residual stresses $\sigma_{res} = \sigma_{eqv} = 160$ MPa in the elastic-plastic body of these steels, considered in the example, is reached at the degree of residual strain of the metal $\varepsilon_{res} \sim 0.0008$ or 0.08 %.

The degree of residual strain ε_{res} received by the metal in the middle part of the arc-shaped plates is estimated from the radius of the circumference R, which can be inscribed in this arc-shaped part (Fig.3). The values of ε_{res} and R are in relation to each other

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$$R = \frac{r}{\varepsilon_{res}}, \qquad (2)$$

where r – distance from the neutral axis to the edge of the plate (half of the thickness), mm.

In accordance with expression (2) at r = 1.5 mm the required level ε_{res} = 0.0008 is achieved by bending the middle part of the plates to the shape of an inscribed circumference with radius R ~ 1.8 m, which for plates of given geometry (150×15 mm) corresponds to the deflection of the plate $H \simeq 8$ mm.

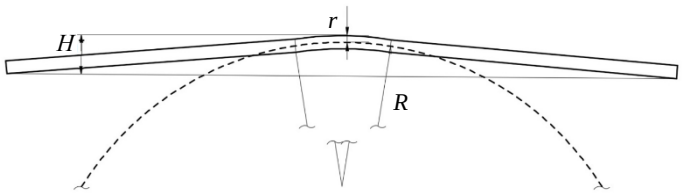


Fig.3. View of a curved plate with the middle part shaped in a circumference of the required radius R, defined using a computer program Autodesk AutoCAD

After bending the plates until the radius R has reached the required value, it is assumed that the metal of the middle plastically deformed part is subject to the same residual stresses as the pipe metal of the field pipeline.

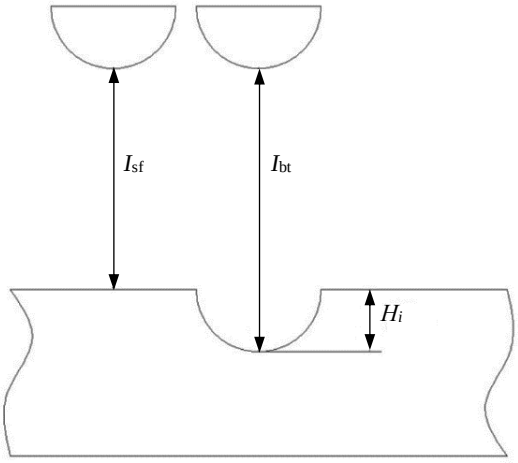


Fig.4. Scheme for determining the depth of cut at a fixed point

Using a 1 mm thick disc shaped cutter with a cutting part in the form of a hemisphere with a radius of 0.5 mm, a crosscut is made in the middle of the plates on the inside with a depth of ~ 0.2 mm and approximately groove-shaped form at the bottom generatrix of the pipeline. Such a cut on a stressed structure serves as a concentrator of additional tensile stresses in the surrounding metal [14, 17, 31] and, as may be concluded, should intensify the corrosion rate. For example, with a cut of 0.2 mm deep on the curved plate of the considered configuration with σ_{res} = 160 MPa residual stress equal to 200 MPa occurs in the metal of the bottom of the cut.

Using a LaboMet-1 optical microscope with a focal length scale step M = 0.003 mm, the exact depth of the cut at the fixed points is determined. For this purpose, the cut along its entire length is optically divided into equal sections, e.g. 1 mm in length. The position of the boundary points (n = 13) is fixed and for each of these the difference in focal lengths in divisions from the bottom of the cut to the plate surface near the cut is determined by rotating the fine adjustment drum $\Delta I = I_{bt} - I_{sf}$ with appropriate recalculation of ΔI (using M) to the original cut depth H_i at that point (Fig.4). To prevent a change in the focal distance to the plate surface near the cut as a result of the corrosive environment, this surface is coated with a protective acetate varnish Ice Color before the corrosion tests.

Conducting the tests. The plates are placed in a thermostat filled with 3 % NaCl aqueous solution as a typical corrosive active medium used both in corrosion investigations, both Russian [5, 15, 20] and foreign [21], to simulate the composition of the aqueous component of oil-water emulsions pumped through the field oil pipelines.

The plates are kept in the solution at 60 ± 5 °C (maximum temperature for pumped water-oil emulsions) for the time sufficient to cause noticeable corrosion of the plates (the recommended duration of exposure according to GOST R 9.905-2007 “Unified system of protection from corrosion and ageing. Corrosion Test Methods. General requirements” is 24; 48; 96 h).

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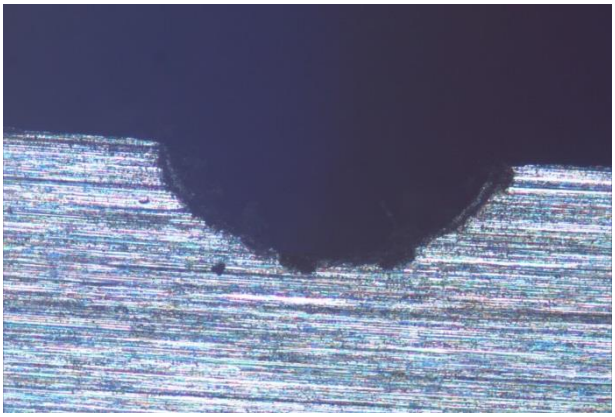


Fig.5. Cross thin section of 09ps steel plate at the cut point after exposure to the environment

During the exposure process, in order to ensure anodic control of the electrochemical reaction, which is necessary to show the effect of the stress state on the corrosion rate, the working solution is enriched with oxygen, which is achieved by continuously blowing air through the solution.

Processing of results. At the end of temperature conditioning, the bottom surface of the plate cut is cleaned from corrosion products with an eraser and the surface of the plates around the cut is cleaned from the protective varnish. At the same points as before the corrosion test, the cut depth of the plates H_i^* is measured again (see table) and its increase ΔH_i is determined as a result of the corrosive effects of the environment (Fig.5). The side surfaces of the plates are polished to obtain thin sections that, after etching, are used for metallographic analysis of the steel.

The arithmetic average of the increase in cut depth for all points is calculated:

$$\Delta H_{\text{av}} = \Sigma \Delta H_i / n, \tag{3}$$

where $n = 13$; mean square deviation

$$S = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\Delta H_i - \Delta H_{\text{av}})^2}, \tag{4}$$

an actual increase in the cut depth is established

$$\Delta H_{\text{act}} = \Delta H_{\text{av}} \pm S \tag{5}$$

and the rate of the grooving corrosion of the plate materials is estimated

$$K = \frac{\Delta H_{\text{act}}}{t} \cdot 8760 = \frac{\Delta H_{\text{av}} \pm S}{t} \cdot 8760, \tag{6}$$

t – time of plates temperature conditioning; 8760 – hours in a year.

The distribution of cut depth changes along its length and the corrosion rates obtained using 09ps and 09G2S pipeline steels as examples are illustrated in the Table.

Cut depths at different points before and after exposure to corrosive environment, change of ΔH_i and values of corrosion rates K of pipeline steels

Plate material	Parameter	Point number n_i												
		1	2	3	4	5	6	7	8	9	10	11	12	13
Steel 09ps	H_i, mm	0.201	0.225	0.240	0.243	0.240	0.237	0.225	0.189	0.174	0.165	0.156	0.135	0.123
	H_i^*, mm	0.210	0.234	0.252	0.255	0.246	0.252	0.231	0.195	0.183	0.180	0.165	0.150	0.141
	ΔH_i, mm	0.009	0.009	0.012	0.012	0.006	0.015	0.006	0.006	0.009	0.015	0.009	0.015	0.018
	$\Delta H_{\text{av}} = 0.011$ mm; $S = 0.0038$ mm; $\Delta H_{\text{act}} = 0.011 \pm 0.0038$ mm; $K = 2.3 \pm 0.8$ mm/year													
Steel 09G2S	H_i, mm	0.195	0.210	0.222	0.219	0.222	0.210	0.195	0.189	0.186	0.186	0.168	0.150	0.144
	H_i^*, mm	0.201	0.219	0.231	0.225	0.231	0.225	0.204	0.195	0.192	0.189	0.174	0.165	0.162
	ΔH_i, mm	0.006	0.009	0.009	0.006	0.009	0.015	0.009	0.006	0.006	0.003	0.006	0.015	0.018
	$\Delta H_{\text{av}} = 0.008$ mm; $S = 0.0044$ mm; $\Delta H_{\text{act}} = 0.008 \pm 0.0044$ mm; $K = 1.8 \pm 0.9$ mm/year													

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By comparing the K values, it can be concluded that 09G2S steel is more resistant to grooving corrosion in comparison with 09ps steel.

In addition to determining the comparative corrosion resistance of steels, the proposed technique allows investigating the effect of tensile and compressive stresses in the metal on the corrosion rate as well as the presence of the cut on the stressed structure. For this purpose, along with the surface of the plate around the cut, a protective varnish is applied to the plastic deformed curved part of the plate on its outer side, where the metal is exposed to compressive stresses, and also to the surface of the unstrained parts of the plate not exposed to any residual stresses. The protective coating is destructed at the indicated places of the plate at local points, the metal in which will be subjected to corrosive effects in subsequent tests. After carrying out corrosion tests, the protective varnish on plate surface around these points is removed. Then the difference in focal distance from the bottom point of the corrosion damage to the unaffected plate surface, taken as the depth of damage at that point, is determined. The necessary dependencies are obtained after performing experiments on plates prepared in this way, pre-curved to different deflection angles.

Conclusion. The technique has been developed for determining the corrosion rate of pipeline steels under conditions simulating corrosion damage of a field pipeline wall: when the pipe wall metal is in a stressed state, the presence of chlorine-ion in the water component of the oil-water emulsion, a channel in the form of a groove is present on the lower generatrix of the pipe, the water component is enriched with air oxygen. As an example for the application of the suggested technique, the corrosion rates of two pipeline steels 09ps and 09G2S were determined. Corrosion rates (2.3 ± 0.8 and 1.8 ± 0.9 mm/year) appeared to be close to those demonstrated by the materials of field pipelines subjected to grooving corrosion. The developed methodology can be used when investigating the effect of tensile and compressive stresses in the metal, as well as the presence of a cut on the stressed structure, on the corrosion rate.

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