Dynamics of Brittle Cracks under the Influence of Low Temperatures

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Abstract. The article contains an investigation methodology of underwater pipelines for transporting hydrocarbons under working loading cycles. The process of hydrogenation of steels occurs with development of brittle cracks under working pressure. The brittle cracks are also caused by the processes of electrochemical corrosion. These transgranular processes lead to an increase in crack formation processes. Controlling the dynamics of brittle cracks allows to control working processes in the underwater main pipelines for transporting hydrocarbons, as well as define measures to maintain stability of underwater pipelines including measures for cathodic protection.

Keywords: Stress corrosion cracking (SCC). Slow strain rate testing (SSRT). Transgranular stress corrosion cracking (TGSCC). Main pipelines

1. Introduction
The underwater main pipeline is an object of increased danger, such as potential risk object, hazardous industrial facility. The analysis of studies statistics regarding corrosion attack under pressure is carried out. Compared to onshore, offshore pipelines are less explosion and fire capable during operation, but damage to offshore pipelines requires complex repair [1].

The underwater main pipelines function under high pressure conditions. Working pressure in the "Nord Stream 2" pipeline system at the inlet is 22 MPa.

Reproduction of "working" loads in the study of engineering system of underwater pipelines is ensured by the requirements formulated in international standards [4-8].

A basic set of requirements can be formulated after summarizing various working conditions of underwater pipelines:

– The impact of the corrosive environment of the pumped product;
– The impact of temperature differences;
– Duration of impact of operational factors;
– Speed dynamics of processes, for example, dynamics of tension – compression along the longitudinal axis of the pipeline.

The composition of steels and mechanical properties of strength of steels, manufacturing technology, alloying conditions, etc. are also important. [2].

The aim of the study is to determine dynamics of brittle cracks under operating conditions that are typical for the underwater main pipeline "Nord Stream-2". We define special operation requirements of the offshore pipeline as the temperature difference and loading cycles that are typical for of pressure drops (mechanical stresses) along the pipeline route [13-14].
2. Materials and methods

Controlled parameters are depth of a defect, nature of a defect, change rate of the controlled sample state [7]. Quantitative characteristics of corrosion processes are based on a qualitative description of observed defects, for example, number of existing and incipient brittle cracks on the unit of samples area. The quality indicators of steel grades for the test conditions are given in Table 1. The table also shows the mechanical parameters and environmental conditions in which the samples are examined.

Table 1. Methodological base of tests in the study of corrosion fracture under pressure

| Steel grade | Test conditions | Test conditions | Cathodic protection potential | Stretch rate | Application area |
|-------------|----------------|----------------|-------------------------------|--------------|------------------|
| Carbon low-alloyed and alloyed constructional steel | 3 % NaCl solution under GOST 4233 | 295 K | 720-3000 hours | 3,6x10^-8 | Different marine conditions |
| Carbon low-alloyed steel 17G1S, 14G2SF, 17G2SAF, a также стали X52-X80 under API 5L standard | 5 % NaCl solution +0.5 % CH₃COOH solution under GOST 19814 | 297 K | 720 hours | 7,2x10^-8 | Sulfur-and-Hydrogen-containing environments |
| Carbon low-alloyed steel 17G1S, 14G2SF, 17G2SAF, a также стали X52-X80 under API 5L standard | 6,5 % NaHCO₃ solution + 6,5 % Na₂CO₃ solution | 295 K | 1000-6000 hours | -695 mV | 3,6x10^-8 | Carbonate, bicarbonate environments |

During cyclic hydrotesting it was found that in the absence of influence of a corrosive environment, development of stress-corrosion cracks with a depth of less than 10% of the pipe wall thickness does not occur [10].

Figure 1 shows crack opening at different load cycles. The crack zones are aligned with the load diagram in % of the permissible stresses σ, working pressure and the load force diagram.
Figure 2 shows tests with holding steel samples in an electrolyte (simulating an aggressive environment). Loads were carried out at the place of application of a U-type concentrator (applied with a cut), loading cycles were carried out with a vibrating machine with a frequency of 0.25 Hz.

![Figure 2](image1.png)

Figure 2. Tests on a tensile testing machine with voltage at the hub site up to $0.99\sigma_T$ with a frequency of 0.25 Hz

During the research 25,000 loading cycles of the sample placed in the electrolyte (a mixture of NS-4 and a borax buffer pH = 7.0) were performed.

The test results were recorded on a metallographic microscope with data processing in a Photolab Siams 700. Figure 3 shows the stages of fatigue crack development with hydrogenation of the sample (the effects of the electrolyte action).

![Figure 3](image2.png)

Figure 3. High-speed photography of a defect on a metallographic microscope with data processing in a Photolab Siams 700: 1-initiation of a defect; 2,3,4 - crack development; 5,6 - the appearance of the effect of hydrogen absorption; 7,8,9,10-change in the structure of steel under loads and hydrogen loading; 11,12,13,14,15-development of destruction of the sample

Fracture mechanics studies were carried out under loading in the longitudinal component with $\Delta\sigma = 50$ MPa and the transverse component with $\Delta\sigma = 40$ MPa. After hydrogenization tensile stresses in the metal reach a level of about 400 MPa, which is quite close to the yield point of pipe steels [12].
3. Results.
The optical morphology of the samples after keeping during 30 days in the tested environment shows visible localized areas of corrosion on the surface of the U-concentrator samples, yellow arrows and dotted lines indicate initiation of microcracks and pits from these areas. The stress-strain state of the U-concentrator sample contributes to initiation of fracturing.

Turning on the AC source allows initiating corrosion to be obtained, and, together with mechanical loading cycles, a synergistic effect is observed that significantly accelerates the local process, which causes the initiation of microcracks and can ultimately cause SCC.

![Figure 4. Surface morphology of U-concentrator samples kept for 30 days with different values of AC current density: (a) 0 A/m²; (b) 10 A/m²; (c) 30 A/m²; (d) 50 A/m²; (e) 100 A/m².](image)

Turning on the AC source leads to an increase in hydrogen density of transfer current and hydrogenization of steel. An increase in hydrogen level in steel leads to the effect of an increase in SCC at various values of $I_y$ and $I_s$.

The mechanism of sample depolarization, caused by the use of alternating current, which has both positive and negative half-waves, causes a cathodic reaction of the samples on the lateral surfaces.

Comparative analysis of primary information about the lateral surfaces, the number of cracks larger than 20 $\mu$m, and the maximum crack length are marked in Figure 5. It can be observed that the number and maximum crack lengths are increasing all the time with increasing current density. The typical number of cracks on the samples obtained under using a power source with the current density of 100 A/m², as well as the maximum crack length (with a length of 321.5 $\mu$m), are shown in Figure 5.

An increase in the alternating current density worsens the process, because microcracks, are apparently observed starting from local dislocation sites at the different values of alternating current marked with yellow arrows in Figure 5 b-e.
Figure 5. Dependences of the microcracks formation on the density of an alternating current of 100 A/m$^2$ during the hydrogenation of the sample: (a) initial stage; (b) an increase in the places of dislocation of cracks; (c) change in the structure of the sample; (d) formation of fracture crack of the sample; (e) is the concentration of dislocations by crack formation; (f) formation of the structure of the fracture crack of the sample.

However, when alternating current density increases to 100 A/m$^2$, size of newly formed cracks decreases, as it is shown in Figure 5f. Nature of the damage indicates predominance of hydrogen in products of electrochemical reactions, which contributes to formation of SCC.

As it can be clearly seen, cracks deepen with alternating current density increasing; the maximum value is 23.9 $\mu$m and appears in the sample with a current density of 100 A/m$^2$, as it is shown in Figure 6. When the alternating current values change, occurs transgranular stress corrosion cracking (TGSCC) in the simulated seawater. The ends of microcracks become sharper with current density increasing due to the cathodic process.
Figure 6. The process of formation of fractures of steel X70 in different specific gravity of alternating current (a) 0 A/m²; (b) 10 A/m²; (c) 30 A/m²; (d) 50 A/m²; and (e) 100 A/m² in the simulated marine environment.

4. Discussion
According to the results of full-scale tests of pipe elements samples there is absence of stress corrosion cracks with a depth of less than 10% of the pipe wall thickness under mechanical loads corresponding to the actual operational ones, provided that electrochemical component of the process is excluded. Crack growth was registered at a pressure of 15.6 MPa.

According to the results of laboratory studies of pipe metal samples with shallow SCC defects the absence of their growth in the manner of the fatigue mechanism was confirmed.

Results of mechanical tests of standard samples indicate compliance of strength properties of the metal from the defective areas with the technical specifications for pipe products.

Residual tension stresses in the pipe metal after its hydrogenation reach a level that is close to the yield point of the tested pipe steel.

5. Conclusions
The obtained results are interesting in process of systematization of data on operation of underwater main pipelines "Nord Stream-2". Study of samples for X70 class pipe steels used in construction of "Nord Stream-2" makes it possible to perform a morphological analysis of brittle fractures under the influence of loading cycles that are typical for operation, influence of the working environment of the pumped product, as well as for cathodic polarization conditions.

It is advisable to predict fracture conditions under working loads using a full-size testing facility under operating conditions and loads. Morphology of surface fractures makes it possible to make a conclusion about the degree of fracturing of the pipeline route in operation.
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