Investigations of resistance to strain corrosion cracking in seawater of the base pipe metal in the construction of the Nord Stream-2

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Abstract. The article studies a method for numerical modeling of the pipeline resistance to corrosion cracking under operating pressure in seawater. Marine geological conditions along the gas pipeline route require a study of the stability of individual sections in the route in terms of occurrence depth and difference in operating temperatures outside and inside a gas pipeline.

Keywords: Offshore underwater main gas pipelines. Hydrogenation of steel samples. Mechanical properties of a pipe base metal. Impact operation at working temperatures. Opening of the crack tip when exposed to temperature (SRT). Destruction energy.

1. Introduction
The offshore underwater pipeline "Nord Stream-2" is built by an international consortium on the bottom of the Baltic Sea. Taking into account a high operating pressure in a pipeline entrance in the Russian territory in Ust-Luga is 220 Bar (22MPa), a wall thickness according to design solutions is 48 mm [1].

Modeling of the pipeline under operating pressure conditions enables to estimate the stress distribution in the pipe body with a check according to a group of strength criteria. A significant factor affecting the stability of the pipeline is the wall thickness with the reinforcement of the weld zone [2].

The most significant factors affecting the stability of the offshore underwater pipeline are the mechanical properties of the pipe base metal in the construction of the Nord Stream-2 pipeline. The mechanical properties include the proportion of the viscous component in the metal, the cold resistance of steels, crack tip opening displacement (CTOD) [3].

The work investigates the pipeline stability at operating pressures and the work of volumetric forces for the pipe base metal of strength group K65 (X70) recommended for the construction of the Nord Stream-2 highway and groups K56 (X60), K50 (X56) similar in strength under the conditions of temperature difference on the outer wall and inside the pipeline [4, 6-8].

The most important qualitative parameter is the prediction of the stability of the pipeline, which contributes calculations for gas transport, as a function of operating pressure reducing in the pipeline. In this aspect, it is possible to make a forecast for the efficiency of gas transportation through the underwater main pipeline "Nord Stream-2" taking into account in terms of economic and environmental risks.

The research involved modeling for pipes with a diameter of 1420 mm, a wall thickness of 48 mm, a strength group K56, an operating pressure P=25.0 MPa, a temperature difference of -20 °C in studies of resistance to stress corrosion cracking in seawater.

Computer modeling provides suitable primary calculations and forecasting, taking into account initial conditions. At the same time, it is useful to study a full-size stability test, in which a stand is usually created.
in conditions close to the operation of an underwater pipeline route [9]. Frequently, a pipeline segment in which working pressure is created inside the pipeline, simulates the work of volumetric forces in the pipeline body and temperature difference [10].

The study of a full-size test, samples of steel of the pipe base metal according to the qualitative characteristics of impact work, the content of a viscous component, cold resistance and cold breakage, CTOD and indirect indicators, for example, crack tip disclosure after flooding of samples constitute a common goal of safe and long-term operation of underwater main pipelines [11-12].

2. Materials and methods
The calculation of the gas pipeline for strength includes the following checks:
- ring stresses;
- longitudinal stresses;
- equivalent stresses.

Determining the stresses and the calculations of the gas pipeline for strength and stability requires to obtain the following values of the physical characteristics of the pipe steel in the elastic area of the pipe material:
- elastic modulus $E_0 = 206000$ MPa;
- Poisson ratio $\mu_0 = 0.3$;
- the coefficient of linear expansion $\alpha = 1.2\cdot10^{-5}$ (°C)-1.

The features of numerical modeling of pipes with a diameter of more than 1120 mm for underwater pipelines should consider [13]:
- a small value of the thick-wall coefficient $\beta$, numerical description of stress distributions and related problems (heat propagation) is difficult to represent by the distribution over the area of the thin wall of the pipeline [14];
- high working pressure, an increase in a diameter that is used in the pipeline gas transport in order to increase the volume of the transported product. The peculiarities of the offshore laying of the pipeline route, the absence of stations for maintaining the working pressure along the entire length of the underwater route should be considered;
- the need to solve a related problem: the distribution of temperature fields, depending on mechanical stresses and operating conditions of the pipeline.

The criterion for evaluating the maximum stresses is taken by Mises. Equivalent voltages are:

$$\sigma_{eq} = \frac{1}{\sqrt{2}} \sqrt{\left(\sigma_r - \sigma_\theta\right)^2 + \left(\sigma_r - \sigma_z\right)^2 + \left(\sigma_\theta - \sigma_z\right)^2},$$

(1)

The calculated stresses of all componentwise loads are summed scalar.

$$\sigma_{vonMises} > \sigma_{limit}$$

(2)

where $\sigma_{vonMises} = \sigma_{eq}$.

The use of the calculation results for assessing the stability according to the Mises criterion is recommended by the STO Gazprom rules 2.2. 1-249-2008.

Let us perform modeling in the ELCUT package SolidWorks with the following conditions: working pressure 7, 4 and 10 MPa, wall thickness 48 mm, outer diameter 1420 mm (Figures 1, 2).

To study the stability properties, we create a geometric model of a pipe with a welded seam cut at the angle 45° inside and outside, as shown in Figure 1.

It should also be taken into account that the weld zone usually demonstrates a strength corresponding to the lowest group. The reason is the inability to obtain conditions for alloying steel in the seam zones when welding the pipe body together. This assumption is considered in the computer model by lowering the requirements for the properties of the steel of the seam zone.
Figure 1. The geometric model for calculating the elastic deformed state of the pipe, with the modeling of the weld

The properties of the pipe materials and the weld body are set according to the conditions of welding materials.

Equivalent stresses, as a function of radial, longitudinal and tangential stresses, depending on the conditions of termination and operation of the gas pipeline, makes it possible to determine the stability of the system according to the calculated parameters.

The model functions enable to set various properties of the material body:
– the base metal of the pipe;
– welded seam;
– reinforcement of the welded seam and its geometry, depending on the technical conditions for welding;
– various defects of pipes in the form of an extended or local heterogeneous section.

Figure 2. Numerical simulation of stress distribution for pipes 1420 mm, 48 mm wall working pressure 10 MPa, strength group K65 (X70), temperature difference –20 °C, heat affected zone of the seam, material properties are specified according to strength group K50

additional stresses arising from uneven loading, leading to deformation of the HAZ of the weld
3. Results
Numerical modeling of the stress distribution of pipelines with a diameter of 1420 mm is performed according to the conditions of the problem of studying corrosion destruction obtained at the stand [5]. The modeling is carried out in the study of resistance to stress corrosion cracking in seawater, including cathodic polarization, base metal and metal of welded joints of steel pipes with a diameter of more than 1120 mm.

The results of numerical modeling are shown in Figure 3. The fracture mechanics studies introduced into the numerical model take into account the loading in the longitudinal component with $\Delta \sigma = 50$ MPa and the transverse component $\Delta \sigma = 40$ MPa.

![Figure 3](image)

Figure 3. Numerical simulation of stress distribution for pipes 1420 mm, wall thickness 48 mm, strength group K56 (X60), working pressure $P = 10,0$ MPa, temperature difference $–20 ^\circ C$ in studies of resistance to stress corrosion cracking under mechanical stresses in line conditions in sea water

The simulation results show that the stability of the pipeline system in conditions of stress corrosion cracking can be ensured by reducing the operating pressure to a value of the order of 100 Bar, while taking into account the depth of the pipeline route and the depth of laying under water.

Simulation with an increase in working pressure up to 25.0 MPa is shown in Figure 4.

![Figure 4](image)

Figure 4. Numerical simulation of stress distribution for pipes 1420 mm, wall thickness 48 mm, strength group K56 (X60), working pressure $P = 25,0$ MPa, temperature difference $–20 ^\circ C$ in studies of resistance to stress corrosion cracking under mechanical stresses in line conditions in sea water

4. Discussion
As follows from the results of numerical simulation of stress distribution under operating pressure conditions, the most significant factor affecting the stability of the system as a whole is the pipeline wall thickness.
The choice of pipes by strength class has a great effect on the parameters of cold resistance and ductile fracture resistance.

Numerical methods can be used to study various modes of loads and stress distributions in pipelines with a diameter of 1420 mm with wall thicknesses up to 48 mm. The choice of boundary conditions and restrictions imposed by the parameters of the model should be studied.

According to the discussed modeling technique, we present the research results for pipelines, the base metal of which corresponds to the strength group K50 (X60). The simulation results are shown in Figures 5 and 6.

Reducing the requirements for the group of steel strength of the pipe base metal under the conditions of the research model for subsea pipelines with a diameter 1420 mm and a wall thickness 48 mm indicates unsatisfactory results at an operating pressure 10 MPa. Simulations indicate pipeline collapse due to operating pressure in the offshore subsea pipeline route conditions as shown in Figures 5 and 6.

### 5. Conclusions
For the underwater main pipeline "Nord Stream-2", the working diameter is 1420 mm and the wall thickness is 48 mm, the strength group of steel in its mechanical properties must correspond to the class K56 (X60).
The conditions for the passage of the offshore subsea pipeline require additional studies of pressure corrosion cracking of steel, CTOD, including the weld zone.

Reducing the requirements for the strength group of steel to the lowest class K50 (X46), as shown by modeling, does not provide stability even when the working pressure is reduced to 10 MPa. At the same time, the initial working pressure in the "Nord Stream-2" is the pressure in the pipeline of 220 MPa. The reasons for the destruction of the route are the work of volumetric forces; the significant factors include the temperature difference inside the pipeline and on the outer wall of the body of the offshore subsea pipeline.

It is useful to supplement the investigated models with data obtained at the stage of laboratory studies of steels of the pipe base metal. Clarification of the strength parameters of the pipe base metal allows creating refined computer models, which are followed by the correction of engineering calculations for the route of underwater offshore pipelines.

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