Approximation of the mechanical characteristics of pipe base metal in the underwater offshore gas pipeline "Nord Stream-2"

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Abstract. The article describes methodological foundations for calculating the mechanical properties of the base metal of pipes: impact work, resistance to corrosion cracking under pressure, crack tip opening displacement at operating temperatures according to the known properties of table parameters "on the left" to unknown parameters "on the right". The calculated values provide an assessment of the system stability during the design and construction of extended offshore underwater pipelines, including a necessary reduction in the safety margin, taking into account hydraulic friction losses during gas pumping.

Keywords: Marine underwater transport systems. Underwater main gas pipelines. Hydraulic friction losses. Mechanical properties of base metal pipes. Impact work. Resistance to pressure corrosion cracking. Crack tip opening displacement. Impact strength. Destruction energy.

1. Introduction

Submarine natural gas transport pipelines are characterized by a considerable length. It is impossible to erect pumping stations along the entire submarine length. Therefore, the pressure at the inlet Ust-Luga of the underwater part of the Nord Stream-2 subsea pipeline is 220 bar.

Greifswald output contains pressure in 108 bar. Pressure difference is accounted by hydraulic friction losses along the entire length of the pipeline. The construction of long underwater routes determines the necessary requirements for the base metal of a pipeline. [2]. These requirements are reduced to the technological capabilities of the production of marine underwater transport systems [1].

An increase in working pressure requires development of standards for the mechanical characteristics of the base metal of pipes used in construction [3]:
- impact work in the transverse direction KV, J;
- resistance to stress corrosion cracking;
- crack tip opening displacement (CTOD) at operating temperatures [5].

The pipeline passes through the territorial waters of several European states and must comply with international requirements for offshore subsea structures of this level of complexity [10].

The Nord Stream 2 pipeline has an internal diameter of 1120 mm and a wall thickness of 40 mm [3]. The aim of the study is to determine a system of requirements for the mechanical characteristics of the base metal steels of the Nord Stream-2 pipeline, which determine the strength and durability of operation [4].

2. Materials and methods

The construction of large-capacity pipelines requires the use of pipes with special characteristics. Operating pressures in the Nord Stream pipeline are 220 bar. The choice of steels and pipes enables to reduce the cost of pumping gas up to 10% under these conditions. Reducing the pipe wall thickness to the limits of...
permissible safe operation up to 15% reduces the cost of pipe steels material, which, when taken into account, increases the efficiency of gas transport up to 15% [3].

Pipe strength is closely related to the parameters of impact toughness, resistance to brittle and ductile fracture, welding technology and quality control of design, construction and operation of trunk pipelines. The strength of the pipe in the transverse direction determines such an important parameter as the maximum allowable pressure in the pipeline; for pipes of strength category X120, the yield strength is $\sigma_{0.2} = 830$ MPa, and the tensile strength is $\sigma_B = 950$ MPa. With such high strength characteristics, it is difficult to achieve high impact toughness, for example, the Nippon Steel Corporation for the base metal X120 regulated the required Charpy fracture energy of 231 J, while the fracture temperature was taken to be -200°C [12].

Taking into account these remarks, the most common strength group of steels for large-diameter pipes are K60, K65 (X70, X80) [13].

The Russian Classification Society supervises the construction and operation of the Nord Stream 2 subsea gas pipeline. Russian Maritime Register of Shipping (RS) defines a set of requirements for large diameter pipe steels [14].

The existing number of mechanical characteristics of the pipe base metal for subsea trunk pipelines in the RS rules is determined up to a pipe wall thickness $t_c < 20$ mm.

Let us determine the parameter "impact work KV", J, in a transverse direction, at $T_r$ -10°C for pipes with $t_c < 20$ mm and at $T_r$ -20°C for pipes with $t_c > 20$ mm. Then we perform the method of approximating the characteristics according to the known distribution "On the left" with the extension of the parameter values to steel grades $1120 \leq D_a \leq 1420$ "to the right".

Approximation of KCV values is carried out according to the "Rules for the construction and classification of subsea pipelines" [3, 6-9]:

$$KCV(D_a) = \sum_{i=0}^{n} KV_i \cdot \prod_{j \neq i}^{n} \frac{D_a - D_{aj}}{D_{ai} - D_{aj}}$$

The calculation data for the KCV approximation are summarized in Table 1.

| Pipeline class G1 - G3 and L3, base metal | PCT3 | PCT3 | PCT4 | PCT42 | PCT46 | PCT50 | PCT55 | PCT62 | PCT69 |
|-----------------------------------------|------|------|------|-------|-------|-------|-------|-------|-------|
| Bran | PCT | W | 2 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $D_a \leq 610$ | 40 | 40 | 50 | 57 | 64 | 73 | 82 | 103 | | | | | | | | | |
| 610 | 40 | 43 | 61 | 69 | 77 | 89 | 100 | 126 | | | | | | | | | |
| $D_a \leq 820$ | 40 | 52 | 75 | 85 | 95 | 109 | 124 | 155 | As agreed with the register |
| 820 | | | | | | | | | | |
| $D_a \leq 1120$ | | | | | | | | | | | | | | | | | | |

As agreed with the register
As agreed with the register

### 3. Results

The calculated values of the parameter impact work KV, obtained by the formula (1) and summarized in Table 1, are comparable with the requirements of Gazprom 2-2-1-249-2008, KCV, the mechanical characteristics of the base metal of pipe steels are correlated with the data in Table 1.

The fracture resistance of the pipeline is characterized by the CTOD parameter. Using formula (1), we calculate the mechanical characteristics at operating temperatures for the entire pipe range. The data are summarized in Table 2.

**Table 2. Interpolation of data on the wall thickness of pipelines and steel grades**

| Brand | CTOD, mm, at Tp, pipeline class LI — L3, GL — G3 |
|-------|-------------------------------------------------|
|       | PCT    | PCT32  | PCT36  | PCT40  | PCT420 | PCT460 | PCT500 | PCT550 | PCT620 | PCT690 |
| W     | W      | W      | W      | W      | W      | W      | W      | W      | W      | W      |

| $t_c$ | 0.10   | 0.10   | 0.10   | 0.10   | 0.10   | 0.15   | 0.15   | 0.15   | 0.20   | 0.20   |
|       |        |        |        |        |        |        |        |        |        |        |

| $t_c$ | 0.15   | 0.20   | 0.20   | 0.25   | 0.20   | 0.35   | 0.35   |        |        |        |
|       |        |        |        |        |        |        |        |        |        |        |

Sulfide stress cracking resistance, pipeline class L2 and G2: no cracking after 720 hours soak at 85% of the minimum normalized yield strength.

Resistance to hydrogen induced/step cracking, pipeline class L2 and G2: CLR ≤ 15%, CTR ≤ 5%, CSR ≤ 2%.

In accordance with the requirements of Gazprom 2-2-1-249-2008, pipes and pipeline fittings (PF) used in the construction of gas trunklines for transporting gas that does not have a corrosive effect on the metal of pipes and PF must meet the requirements of technical specifications, national and international standards, the application of which at the facilities of Gazprom is agreed in accordance with the established procedure [4].

The Batelli Institute introduces the concept of 85% weight security, named semi-empirical criterion Shear Area. The criterion regulates the temperature distribution of strength under operational loads. The criterion characterizes the minimum energy level of Charpy destruction (impact work), taking into account the axial defects of the pipes.
Table 3. Requirements for impact toughness KCV and KCU of pipe and PF metal to ensure resistance to crack initiation and propagation

| Strength class | Impact strength of the base metal, ≥ J/cm² | Impact toughness of the welded joint, ≥ J/cm² |
|----------------|------------------------------------------|---------------------------------------------|
|                | tube (KCV)                               | PF                                         |
|                |                                        | tube (KCV)                                 | PF                                         |
| K65            | 70                                      | 50 (KCV)                                   | 60 (KCV)                                   |
|                | 69                                      | 59 (KCU)                                   | 49 (KCV)                                   |
| K60            | 55                                      | 50 (KCV)                                   | 50 (KCU)                                   |
|                | 50                                      | 50 (KCU)                                   | 49 (KCV)                                   |
| K56            | 50                                      | 50 (KCV)                                   | 35 (KCU)                                   |
|                | 50                                      | 50 (KCU)                                   | 35 (KCU)                                   |
| K50-K54        | 45                                      | 45 (KCV)                                   | 35 (KCU)                                   |
|                | 45                                      | 45 (KCU)                                   | 35 (KCU)                                   |
| K42-K48        | 35                                      | 35 (KCV)                                   | 35 (KCU)                                   |
|                | 35                                      | 35 (KCU)                                   | 35 (KCU)                                   |

Requirements for impact strength are established in technical requirements, technical conditions, taking into account the operating conditions of the gas pipeline and the results of qualification tests. These requirements can be set more stringent than the requirements of the table.

Almost all projects of transport oil and gas pipelines in Europe and Canada with a rather cold climate were provided by the research of the Batelli Institute.

The equations of NG-18 Batteli Institute are applicable when the Charpy fracture criterion level is over 40 J. The initiator of the fracture is the working pressure in the pipeline and the axial extended pipe defect, according to the initiator of fracture-notch defect (CTOD):

\[
\frac{\sigma_f}{\sigma_0} = \left(1 - \frac{d}{t} + \frac{d}{(M \cdot t)}\right)^{1/2},
\]

where \(\sigma_f\) is a fracture stress; \(\sigma_0\) is a stress of plastic deformations of the material; \(d\) is the depth of the defect; \(t\) is the pipe wall thickness; \(M\) is an empirical factor (deviation) influencing the increase in stress at the ends of defects, consisting of an external radial deflection along the defect initiating fracture.

\[
\sigma_0 = \frac{(YS + TS)}{2},
\]

where \(YS\) is the yield point, \(TS\) is the tensile strength.

\[
M = \sqrt{1 + 0.4025 \cdot \left(\frac{2C}{R}\right)^2},
\]

where \(2C\) is the length of the defect; \(R\) is the radius of the pipe.

With the group "X" of strength of pipe steels up to X70, studies on full-scale tests showed the correspondence of Batelli formulas for fracture stress values of 0.87 and impact work KCV in the range of 30-130 J.

For steels of strength groups above X70, obtained by TMCP methods, the values of yield and tensile stresses constitute 0.93 of those obtained experimentally, at KCV - 200 J.

Further refinement will lead to errors in the lower values of mechanical properties caused by the stabilizing property of the exponential distribution of stresses and the lower level of plastic deformation in the defect zone. All these factors underestimate the parameters of the mechanical properties of steels.

4. Discussion

The obtained results enable to draw several practically important conclusions.

The application of the approximation of the characteristics in the previously obtained values of the mechanical indices of the pipe base metal for the next in size range of assortments used in the construction
of offshore subsea pipelines corresponds to a number of standards used for the construction of Gazprom and calculations using the Batteli Institute formulas.

Investigation of the stability of subsea pipelines gives the best results during a full-scale hydraulic test type to determine the lower limits of \( Y/T \), with different indicators of the depth defect ratio to its length.

The study of the calculated values of the mechanical properties of the base metal of pipes, summarized in Tables 1-3 allow to use them in practical calculations in the design of offshore subsea pipelines.

5. Conclusions
Calculation of the mechanical characteristics of the pipe base metal used in the construction of offshore subsea pipelines can be performed according to the actual parameters of pipe assortments similar in properties to steels according to the sets of parameters of the series "on the left" to the next parameter "on the right".

Calculations can be verified using the Batteli empirical formulas.

The mechanical properties of low-alloy steels used in the construction of offshore subsea pipelines provide a linear approximation of the mechanical properties of steels, similar to the alloying technologies used in the manufacture of strip.

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