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RESEARCH ARTICLE

CALCULATION OF VESSEL LIFE TO MACROCRACK FORMATION UNDER PULSATING INTERNAL PRESSURE

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Abstract. *The reliability and durability of metal components in engineering systems and special structures operating under internal pressure depend significantly on changes in material's mechanical properties under the combined effects of cyclic loads, elevated temperatures, and a corrosive environment. This study's aim: to develop a methodology for calculating the durability of a vessel subjected to variable pressure, accounting for the influence of a corrosive environment on the material's mechanical properties. 10GN2MFA steel's mechanical properties were determined through static tensile testing at 10^{-3} - 10^{-6} s⁻¹ strain rates in air and distilled water at 280°C, using equipment with a high-pressure chamber. It was found that the steel's ductility in high-temperature distilled water decreases significantly at 10^{-4} - 10^{-6} s⁻¹ strain rates, reaching a minimum at $\dot{\epsilon} = 10^{-6}$ s⁻¹. Based on strain-based criteria for low-cycle failure, the number of loading cycles to macroscopic crack initiation was calculated. Given a certain deformation time proportion within the critical strain rate range, the calculated durability in the corrosive environment is 19-20% lower than in air. The work's scientific novelty: the development of a methodology for calculating durability up to macroscopic crack initiation using steel ductility characteristics determined in a high-temperature corrosive environment. Unlike standard approaches based primarily on mechanical properties determined in air, the methodology accounts for changes in ductility caused by the operating environment. The practical significance: the potential to apply the approach to calculate the durability of metal components operating under internal pressure subject to the combined effects of cyclic loads, elevated temperatures, and a corrosive environment.*

Keywords: *metal structures; engineering systems; high-pressure vessel; low-cycle durability; corrosive environment; ductility; crack formation; strain rate.*

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ПУЛЬСТІ ІШКІ ҚЫСЫМ ӘСЕРІНДЕГІ ЖОҒАРЫ ҚЫСЫМДЫ СОСУДТЫҢ МАКРОЖАРЫҚШАҚ ТҮЗІЛУІНЕ ДЕЙІНГІ ҰЗАҚМЕРЗІМДІЛІГІН ЕСЕПТЕУ

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Аңдатпа. Ішкі қысыммен жұмыс істейтін инженерлік жүйелер мен арнайы құрылыстардың металл элементтерінің сенімділігі мен ұзаққа төзімділігі циклдік жүктемелердің, жоғары температураның және коррозиялық ортаның бірлескен әсерінен материалдың механикалық қасиеттерінің өзгеруіне тәуелді. Жұмыстың мақсаты - коррозиялық ортаның корпус материалының механикалық қасиеттеріне әсерін ескеріп, айналымы қысымдағы ыдыстың ұзаққа төзімділігін есептеу әдістемесін әзірлеу. 10ГН2МФА болатының механикалық қасиеттері жоғары қысымды камерасы бар қондырғыда 280 °С температурада ауада және дистилденген суда, 10^{-3} - 10^{-6} с⁻¹ деформациялау жылдамдықтарында статикалық созу арқылы анықталды. Жоғары температурадағы суда болаттың пластикалылығы 10^{-4} - 10^{-6} с⁻¹ деформациялау жылдамдықтарында едәуір төмендеп, $\dot{\epsilon} = 10^{-6}$ с⁻¹ критикалық жылдамдықта ең төменгі мәнге жететіні анықталды. Аз циклді бұзылудың деформациялық критерийлері негізінде макроскопиялық жарықшақ пайда болғанға дейінгі жүктеме циклдерінің саны есептелді. Деформациялану уақытының белгілі бір бөлігі критикалық жылдамдықтар аймағына сәйкес келгенде, коррозиялық ортадағы есептік ұзаққа төзімділік ауадағыдан шамамен 19–20%-ға төмен болады. Ғылыми жаңалық жоғары температуралы коррозиялық ортада тікелей эксперименттік жолмен анықталған болаттың пластикалылық сипаттамалары негізінде макроскопиялық жарықшақ пайда болғанға дейінгі ыдыстың ұзаққа төзімділігін есептеу әдістемесін әзірлеуде. Негізінен материалдың ауадағы механикалық сипаттамаларына сүйенетін нормативтік тәсілден айырмашылығы, әдістеме жұмыс ортасының әсерінен пластикалылықтың өзгеруін ескереді. Практикалық маңыздылығы - тәсілді циклдік жүктемелер, жоғары температура және коррозиялық орта бірлесіп әсер еткенде ішкі қысыммен жұмыс істейтін металл элементтердің ұзаққа төзімділігін бағалауға қолдану мүмкіндігі.

Түйін сөздер: жоғары қысымды сосуд; төмен циклді шаршау; қайталама статикалық жүктеме; коррозиялық орта; ұзақмерзімділік; макрожарықшақ; деформациялану жылдамдығы.

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НАУЧНАЯ СТАТЬЯ

РАСЧЕТ ДОЛГОВЕЧНОСТИ СОСУДА ВЫСОКОГО ДАВЛЕНИЯ ДО ОБРАЗОВАНИЯ МАКРОТРЕЩИНЫ ПРИ ПУЛЬСИРУЮЩЕМ ВНУТРЕННЕМ ДАВЛЕНИИ

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Аннотация. *Надежность и долговечность металлических элементов инженерных систем и специальных сооружений, работающих под внутренним давлением, зависят от изменения механических свойств материала при совместном воздействии циклических нагрузок, повышенной температуры и коррозионной среды. Цель работы - разработать методику расчета долговечности сосуда при переменном давлении с учетом влияния коррозионной среды на механические свойства материала корпуса. Механические свойства стали 10ГН2МФА определены статическим растяжением при скоростях деформирования 10^{-3} – 10^{-6} с⁻¹ на воздухе и в дистиллированной воде при 280 °С на установке с камерой высокого давления. Установлено существенное снижение пластичности стали в высокотемпературной воде при скоростях деформирования 10^{-4} – 10^{-6} с⁻¹ с минимумом при критической скорости $\dot{\epsilon} = 10^{-6}$ с⁻¹. По деформационным критериям малоциклового разрушения рассчитано число циклов нагружения до образования макроскопической трещины. При определенной доле времени деформирования в области критических скоростей расчетная долговечность в коррозионной среде примерно на 19–20% ниже, чем на воздухе. Научная новизна заключается в разработке методики расчета долговечности сосуда до образования макроскопической трещины на основе характеристик пластичности стали, экспериментально определенных непосредственно в высокотемпературной коррозионной среде. В отличие от нормативного подхода, основанного преимущественно на механических характеристиках материала на воздухе, методика учитывает изменение пластичности под воздействием рабочей среды. Практическая значимость - возможность применения подхода для оценки долговечности металлических элементов под внутренним давлением при совместном воздействии циклических нагрузок, повышенной температуры и коррозионной среды.*

Ключевые слова: *сосуд высокого давления; малоцикловая усталость; повторно-статическое нагружение; коррозионная среда; долговечность; макротрещина; скорость деформирования.*

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1 INTRODUCTION

The reliability and durability of metal structures and components within building engineering systems are crucial factors in ensuring the safety of construction projects. This issue is of particular importance for metal components that operate under internal pressure and are subjected, during service, to the combined effects of cyclic mechanical loads, elevated temperatures, and the working medium. Such components include vessels and pipelines for heating and water supply systems, heat-exchange and process equipment, as well as elements of special engineering structures, where changes in material mechanical properties during operation can significantly impact strength and durability.

Performing engineering calculations regarding the strength and durability of such structures requires reliable data on the nature of operational loading, operating temperature conditions, the properties of the surrounding and working environments, the stress-strain state of the most highly loaded areas, and the physicochemical and mechanical properties of the structural material. Of particular importance are computational models that enable the assessment of the service life of structures, both those being designed and those currently in service, based on these parameters.

During prolonged service, the initial mechanical properties of structural materials may change due to the combined effects of temperature, corrosive environments, and cyclic mechanical loads. A reduction in material strength and ductility directly influences the processes of damage accumulation and crack formation. Therefore, when calculating the durability of metal structural elements operating under complex thermal and mechanical conditions, it is essential to consider material properties that correspond to actual operating conditions.

This issue is particularly relevant for vessels and pipelines in power generation units, equipment used in chemical and petrochemical processing, and other metal components of engineering systems and special structures subject to stringent reliability and safety requirements. Accurately determining their service life requires data not only on the material's initial mechanical properties but also on how these properties change due to prolonged exposure to the operating environment, temperature, and cyclic loading.

In current engineering practice, calculations are frequently performed using standard mechanical property values determined primarily in an air environment. Any potential reduction in material strength and ductility under actual service conditions is compensated for by applying safety factors and allowances for corrosion damage. However, this approach does not fully characterize changes in the material's deformation capacity under the direct influence of a corrosive environment and may affect the accuracy of structural durability assessments.

This issue is of particular importance when assessing the technical condition and residual service life of metal components subjected to prolonged internal pressure. Obtaining experimental material characteristics under conditions closely approximating actual service allows for accounting for the influence of the operating medium on strength and ductility, and utilizing this data for durability calculations.

Due to the non-stationary nature of thermal and mechanical service loads, vessels and pipelines may be subjected to repeated static variable loads; the nature of their variation over time corresponds to low-cycle loading of the material. Under such conditions, the damage accumulation process depends not only on stress and strain levels but also on the material's plastic characteristics, the strain rate, and the parameters of the operating medium.

The total durability of a structural element under cyclic loading can be conditionally divided into two sequential stages: damage accumulation leading to the formation of a macroscopic crack, and the subsequent propagation of that crack until it reaches a critical size. This study focuses on the first stage, estimating the number of loading cycles required to initiate a macroscopic crack, while accounting for changes in material ductility within a high-temperature corrosive environment.

The aim of this study is to develop a methodology for calculating the durability, up to the point of macroscopic crack initiation, of a metal vessel operating under pulsating internal pressure,

taking into account the experimentally determined effects of a high-temperature corrosive environment and strain rate on the material's plastic properties. The proposed approach is evaluated in terms of its applicability to assessing the service life of metal components in engineering systems and special structures operating under comparable conditions of cyclic loading, elevated temperatures, and exposure to corrosive environments.

Strength calculation of high-pressure vessels is one of the key stages of their design, as the reliability and operational safety of the equipment are determined by the vessel's ability to withstand internal pressure, temperature effects, and cyclic mechanical loads. According to GOST R 54522-2011 "High-Pressure Vessels and Apparatuses. Strength Calculation Standards and Methods", the wall thickness of cylindrical shells is calculated primarily based on static strength conditions, taking into account internal pressure, geometric design parameters, permissible material stresses, and the strength factor of welded joints [1].

The calculated wall thickness of a cylindrical shell is determined based on the condition of ensuring strength under maximum operating pressure. This takes into account the effect of wall thickness on stress distribution and uses a design thickness factor. After determining the wall thickness, verification calculations are performed, including an assessment of the strength under cyclic loading and the determination of the permissible number of operating cycles for the structure.

However, standard calculations are primarily based on the mechanical properties of the material determined in air. The effects of a corrosive environment are typically accounted for by adding a corrosion allowance, reducing the actual wall thickness, or introducing coefficients characterizing the operating conditions. However, the potential change in the plastic properties of the material directly in the operating environment may not be fully accounted for. For vessels operating at elevated temperatures and in contact with an aqueous medium, this factor can have a significant impact on the accumulation of fatigue damage and the formation of macroscopic cracks.

Contemporary research focuses on the corrosion fatigue of structural steels operating in high-temperature water. It was established that the combined effects of cyclic loading and a corrosive environment lead to a reduction in durability compared to air testing. The severity of corrosion fatigue damage is influenced by ambient temperature, strain rate, strain amplitude, cycle asymmetry coefficient, dissolved oxygen concentration, and the chemical composition of the material. Proposed a corrosion fatigue model for stainless steels used in high-temperature pressurized water [2, 3]. The model's development took into account temperature, strain rate, and dissolved oxygen content, which all influence the reduction in fatigue life of the material.

Studies of the influence of strain rate are particularly important for durability calculations. As strain rate decreases, the duration of interaction between the metal surface and the corrosive environment during each cycle increases. This promotes electrochemical processes, localized destruction of protective oxide films, and the accumulation of damage in the surface layers of the material. As a result, the ductility of the steel may decrease, reducing the number of cycles before fatigue crack formation. Therefore, relying solely on mechanical properties obtained from air testing may lead to an overestimation of the durability of components operating in a corrosive environment.

Modern research shows that high-temperature water has a significant impact not only on the growth rate of existing cracks but also on the stage of their initiation. Studied the behavior of stainless steels during fatigue crack development in water at 325°C and high pressure. The results confirm the need to consider the parameters of the aqueous environment when assessing a material's resistance to cyclic fracture [4].

A paper by, published in 2025, examined the prediction of the corrosion-fatigue life of austenitic steels. The authors note that high-temperature pressurized water reduces fatigue life due to the combined effects of cyclic strain and corrosion processes. The amplitude and rate of strain, the cycle asymmetry coefficient, temperature, the pH of the environment, and the concentrations of dissolved oxygen and hydrogen all have significant effects [5].

Current research also develops numerical methods for modeling the transition of corrosion damage to a fatigue crack. Specifically, the transition from a localized corrosion defect to a crack is

considered, taking into account the random nature of the formation and development of corrosion damage. It is shown that the geometry and shape of corrosion defects significantly influence the local stress and strain concentration and, consequently, the moment of fatigue crack initiation [6, 7].

For structures operating under repeated static pulsating internal pressure, durability is best considered as a combination of two sequential stages. The first stage involves the accumulation of cyclic damage, localization of plastic strain, and the formation of a macroscopic crack. The duration of this stage is determined by the cyclic strength and ductility characteristics of the material, the stress level, the loading cycle parameters, and the conditions of exposure to a corrosive environment. The second stage begins after the formation of a macrocrack and is characterized by its subsequent growth until it reaches a critical size. At this stage, durability is determined by fracture mechanics methods using the dependence of the crack growth rate on the stress intensity factor.

Thus, the overall durability of a vessel under cyclic loading can be represented as (1):

$$N = N_n + N_r, \quad (1)$$

where N_n - the number of cycles before a macroscopic crack forms; N_r - the number of crack growth cycles before reaching a critical size.

This paper examines the first stage of service life, corresponding to damage accumulation and the formation of a macroscopic corrosion-mechanical crack. This stage is assessed using low-cycle failure strain criteria, which take into account the plastic component of cyclic strain. This approach is justified for vessels operating under significant stress levels and a limited number of loading cycles [8, 9].

An analysis of modern research shows that existing methods for calculating corrosion fatigue life are primarily focused on the use of empirical correction factors, numerical modeling, or assessment of the development of existing cracks. However, the direct use of ductility characteristics experimentally determined in a corrosive environment under parameters corresponding to vessel operating conditions has been insufficiently studied. Furthermore, the influence of strain rate on changes in the plastic properties of steel and on the number of cycles before macroscopic crack formation requires additional experimental and computational justification [10, 20, 21].

Therefore, the development of a method for calculating the life of a high-pressure vessel body before macrocrack formation, based on experimentally determined material ductility characteristics in a high-temperature corrosive environment, is relevant. Using material characteristics directly obtained under operating conditions will improve the reliability of low-cycle life predictions and assess the degree of vessel service life reduction under pulsating internal pressure [11, 12, 19].

2 MATERIALS AND METHODS

In engineering calculations of low-cycle strength, the standard low-cycle fatigue calculation model is currently used as an engineering method to determine the durability at the stage preceding macrocrack formation. Along with the strength characteristics R_m , $R_{p0.2}$, the strain characteristics of the material, namely the ductility indicator (ψ), is also taken into account.

The number of loading cycles N_T before a macrocrack forms during the operation of a structure in an air environment using the low-cycle rigid loading criterion is calculated using the Coffin-Manson equations [13, 14].

It should be noted that, according to this calculation model, a minor change in the material's ductility characteristics significantly affects the durability calculation results.

Therefore, the objective of the research was to study the influence of certain operational factors on the mechanical properties of steels widely used in power engineering and chemical apparatus engineering. A corrosive environment has the most significant impact on the mechanical

properties of materials, since no element of any existing metal structure is immune to contact with a corrosive environment [15, 16,17].

To illustrate the selected calculation model, which uses material properties characterizing its strain capacity, the estimated durability of a thick-walled vessel operating under internal pressure in an aqueous environment was determined. The vessel material was low-carbon, low-alloy 10GN2MFA grade steel. The low-alloy, high-strength, and heat-resistant 10GN2MFA grade steel is used to manufacture steam generator bodies and headers that come into contact with the primary-circuit water of nuclear power plant reactors. Its operating temperature range is 280°C to 350°C. To assess the effect of high-temperature water, the patterns of change in the ductility of this steel grade at a distilled water temperature of 280°C and a pressure of 15 MPa were experimentally investigated using a special high-pressure chamber. This temperature was selected based on the occurrence of corrosion fatigue cracks on the surface of the cold header, where the body temperature is 280°C. The material for the test samples was obtained from NPO TsNIITMASH (Moscow) during the implementation of Task 01.07 under Targeted Comprehensive Program O.Ts. 001 of the USSR State Committee for Science and Technology, the USSR State Planning Committee, and the USSR Academy of Sciences. Chemical analysis confirmed that the composition of the samples matches the specifications for this steel grade as defined in Technical Specification TU 0893-014-00212179-2004; the chemical composition is presented in Table 1.

The standard mechanical properties determined on samples with a diameter $d_o = 10\text{mm}$, are as follows: yield strength $R_{p0.2} = 415\text{MPa}$, tensile strength $R_m = 545\text{MPa}$, and relative contraction of the transverse constriction area $\psi = 77\%$.

Table 1 - Chemical composition of 10GN2MFA grade steel (mass fraction, %).

C	Mn	Si	Ni	S	P	Cr	Mo	V	Cu
0.08-0.12	0.8-1.1	0.17-0.37	1.8-2.3	to 0.02	to 0.02	to 0.3	0.4-0.7	0.03-0.07	to 0.3

The tests were conducted on cylindrical samples made of 10GN2MFA grade steel with M18×1.5 threaded heads, a 10 mm gauge section diameter, a 40 mm gauge section length, and an overall length of 100 mm (Figures 1 and 2).

The experimental samples were machined from rolled metal products. Cooling and machining conditions were selected to prevent any changes in the steel properties due to heat generated during the machining process. The geometry and key dimensions of the samples are detailed in the authors' previously published paper [15].

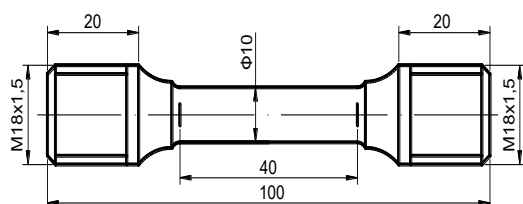


Figure 1 - Shapes and geometric dimensions of the test sample. [Author's material]

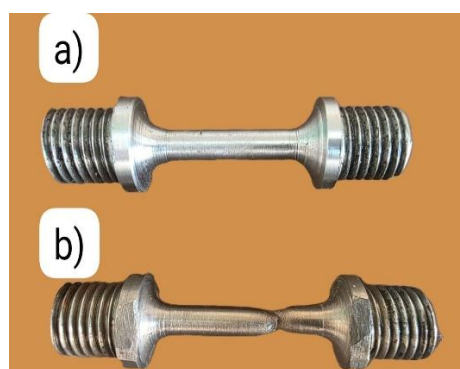


Figure 2 - Test samples

a) before testing
b) after testing. [Author's material]

Experimental studies were conducted using a specially designed test rig (Figure 3), the design and operating principle of which are described in detail in [16]. The rig enables sample testing in distilled water at temperatures up to 300°C and pressures up to 15 MPa, while maintaining the specified environmental parameters throughout the test. In the present study, the distilled water temperature was 280°C and the pressure was 15 MPa.

The distilled water used in the experiment was produced via distillation at the accredited “Regional Test Laboratory of Engineering Profile “Structural and Biochemical Materials”. The chemical composition of the distilled water, specifically the levels of oxygen and other impurities, was not monitored separately, as all laboratory equipment and instruments, including the water distiller, held the appropriate accreditation. The temperature was maintained automatically using an electric heater and monitored by a temperature sensor. Chamber pressure was monitored via a pressure gauge and maintained at the set level throughout the test [16].

After the sample was installed, the test chamber (Figure 4) was filled with distilled water, and the specified pressure and temperature conditions were established. Once the target environmental parameters were reached, the sample was subjected to tension at a constant strain rate. During the test, the applied force and the corresponding sample deformation were recorded. Testing continued until sample damage, after which the residual elongation of the gauge section and the sample diameter at the necking zone were measured to determine ductility characteristics. The detailed testing procedure is described in [16].

Cyclic deformation tests were conducted using a symmetrical cycle under “soft” loading conditions, with strain amplitudes ranging from 0.4% to 1.6%, to generate a low-cycle fatigue curve. Three samples were tested at each strain level. Force and deformation were determined during the test using pre-established calibration relationships. Force was measured based on the signal from the inductive displacement transducer of a mechanical extensometer mounted inside the load rod. The calibration relationship between the sensor signal and axial force was established using a DOSM-3 reference dynamometer and a KSP-4 millivoltmeter. Sample deformation was determined using a separate calibration relationship between load rod displacement and the deformation of the sample’s gauge section; this relationship was established by monitoring rod displacement with dial indicators having a resolution of 0.001 mm [16].



Figure 3 - Test rig. [Author's material]



Figure 4 - Test chamber. [Author's material]

A 240 mm diameter branch pipe with a 32 mm thickness wall is welded into a 52 mm thickness wall with a 920 mm diameter wall vessel. The nominal stress induced in the vessel wall by the

environment pressure is 312MPa . The theoretical stress concentration factor at the branch pipe joint is $\alpha_\sigma = 2,35$.

The estimated values of the hardening index ν under single static loading are determined (if $e \geq R_e^t/E^t$) using the formula (2) from [18].

$$\nu = 0,75 * \nu' = 0,75 * 0,171 = 0,128 \quad (2)$$

$$\text{where: } \nu' = 0,75 * \frac{\lg[R_m / R_{p0.2} * (1 + 1,4\nu)]}{\lg\left[\left(10^5 * \ln \frac{1}{1-\nu'}\right) / (200 + 0,5R_{p0.2})\right]} = 0,171 \quad (3)$$

Then the calculated material properties obtained by testing a sample with a diameter of 52 mm, corresponding to the vessel thickness, are determined by the following formula (4):

$$R_{p0.2} = (R_{p0.2})_o * \left(\frac{d_o^2}{d^2}\right)^{m_{0.2}} = 415 * \left(\frac{10^2}{52^2}\right)^{0,013} = 398\text{MPa} \quad (4)$$

Yield strength (5) (elastic limit at 0.02% deformation),

$$R_m = (R_m)_o * \left(\frac{d_o^2}{d^2}\right)^{m_{0.2}} = 545 * \left(\frac{10^2}{52^2}\right)^{0,013} = 523\text{MPa} \quad (5)$$

Ultimate tensile strength (ultimate resistance).

Cross-sectional contraction coefficient (6)

$$\psi^T = \psi_o^T * \left(\frac{d_o^2}{d^2}\right)^{m_\psi} = 0,77 * \left(\frac{10^2}{52^2}\right)^{0,04} = 0,67 \quad (6)$$

The yield strength R_e for the vessel material is determined by the following formula (7):

$$\sigma_T = \left[\frac{R_{p0.2}}{(E * 0,2 * 10^{-2} + R_{p0.2})^\nu}\right]^{1/(1-\nu)} = \left[\frac{398}{(1,96 * 10^5 * 0,2 * 10^{-2} + 398)^{0,17}}\right]^{1,2} = 348\text{MPa} \quad (7)$$

Then the deformation corresponding to the yield strength will be equal to (8)

$$e_T = \frac{\sigma_T}{E} = \frac{348}{1,96 * 10^5} = 0,00177 \quad (8)$$

The ultimate relative strain is determined by the formula (9)

$$\bar{e}_k = \frac{1}{e_T} \ln \frac{1}{1-\psi} = \frac{1}{0,00177} \ln \frac{1}{1-0,67} = 626 \quad (9)$$

The cyclic yield strength is assumed to be equal to (10)

$$\bar{S}_T^{(k)} = \bar{S}_T^{(1)} = 2\bar{\sigma}_T = 2 \quad (10)$$

The relative values of the nominal principal stresses (11), (12), (13)

$$\bar{R}_{1n} = \frac{R_{1n}}{R_e} = \frac{312}{348} = 0,896 \quad (11)$$

$$\bar{R}_{2n} = 0,5\bar{R}_{1n} = 0,5 * 0,896 = 0,448 \quad (12)$$

$$\bar{R}_{3n} = 0 \quad (13)$$

The intensity of the relative nominal stresses is determined by the formula (14)

$$\begin{aligned} \bar{\sigma}_{in} &= \frac{1}{\sqrt{2}} * \bar{\sigma}_{1n} \sqrt{\left(1 - \bar{\sigma}_{2n}\right)^2 + \left(\bar{\sigma}_{2n} - \bar{\sigma}_{3n}\right)^2 + \left(\bar{\sigma}_{3n} - 1\right)^2} = \\ &= \frac{1}{\sqrt{2}} * 0,896 \sqrt{(1-0,5)^2 + (0,5-0)^2 + (0-1)^2} = 0,77 \end{aligned} \quad (14)$$

$$\bar{\sigma}_{2n} = \frac{\bar{\sigma}_{2n}}{\bar{\sigma}_{1n}} = \frac{0,448}{0,896} = 0,5 \quad (15)$$

$$\bar{\sigma}_{3n} = \frac{\bar{\sigma}_{3n}}{\bar{\sigma}_{1n}} = \frac{0}{0,896} = 0 \quad (16)$$

The intensity of the nominal deformations will be equal to (17)

$$\begin{aligned} \bar{e}_{in} &= \frac{\sqrt{2}}{3} * \bar{\sigma}_{in} (1 + \mu) \sqrt{\left(1 - \bar{\sigma}_{2n}\right)^2 + \left(\bar{\sigma}_{2n} - \bar{\sigma}_{3n}\right)^2 + \left(\bar{\sigma}_{3n} - 1\right)^2} = \\ &= \frac{\sqrt{2}}{3} * 0,896 (1 + 0,3) \sqrt{(1-0,5)^2 + (0,5-0)^2 + (0-1)^2} = 0,66 \end{aligned} \quad (17)$$

The maximum conditional elastic stresses in the stress concentration zone are determined by (18), (19), (20)

$$\bar{\sigma}_{1\max} = \alpha_{\sigma} * \bar{\sigma}_{1n} = 2,35 * 0,896 = 2,11 \quad (18)$$

$$\bar{\sigma}_{2\max} = \alpha_{\sigma} * \bar{\sigma}_{2n} = 2,35 * 0,448 = 1,05 \quad (19)$$

$$\bar{\sigma}_{3\max} = 0 \quad (20)$$

Then the relative values of local stresses will be equal to (21), (22)

$$\bar{\sigma}_{2\max} = \bar{\sigma}_{2\max} / \bar{\sigma}_{1\max} = \frac{1,05}{2,11} = 0,5 \quad (21)$$

$$\bar{\sigma}_{3\max} = \bar{\sigma}_{3\max} / \bar{\sigma}_{1\max} = \frac{0,0}{2,11} = 0 \quad (22)$$

Local stress intensity (23)

$$\begin{aligned}\bar{\sigma}_{i\max} &= \frac{1}{\sqrt{2}} * \bar{\sigma}_{1\max} \sqrt{\left(1 - \bar{\sigma}_{2\max}\right)^2 + \left(\bar{\sigma}_{2\max} - \bar{\sigma}_{3\max}\right)^2 + \left(\bar{\sigma}_{3\max} - 1\right)^2} = \\ &= \frac{1}{\sqrt{2}} * 2,11 \sqrt{(1-0,5)^2 + (0,5-0)^2 + (0-1)^2} = 1,83\end{aligned}\quad (23)$$

$$\text{Coefficient } \mu_{\max} = 0,5 - \frac{0,2}{\alpha_{\sigma}^{2(1-\nu)/(1+\nu)}} = 0,5 - \frac{0,2}{2,35^{2(1-0,17)/(1+0,17)}} = 0,449 \quad (24)$$

Then the local strain intensity will be equal to (25)

$$\begin{aligned}\bar{e}_{i\max} &= \frac{\sqrt{2}}{3} * \bar{\sigma}_{1\max} (1 + \mu_{\max}) \sqrt{\left(1 - \bar{\sigma}_{2\max}\right)^2 + \left(\bar{\sigma}_{2\max} - \bar{\sigma}_{3\max}\right)^2 + \left(\bar{\sigma}_{3\max} - 1\right)^2} = \\ &= \frac{\sqrt{2}}{3} * 2,11 (1 + 0,449) \sqrt{(1-0,5)^2 + (0,5-0)^2 + (0-1)^2} = 1,82\end{aligned}\quad (25)$$

Strain concentration factor in the zero half-cycle (26)

$$k_e^o = \frac{\alpha_{\sigma}^{2/(1+\nu)} * \bar{\sigma}_{in}^{(1-\nu)/(1+\nu)}}{(\alpha_{\sigma} * \bar{\sigma}_{in})^{n(1-\nu)[\bar{\sigma}_{in} - (1/\alpha_o)]/(1+\nu)}} = 3,517 \quad (26)$$

Stress concentration factor in the zero half-cycle (27)

$$k_{\sigma}^o = \frac{\alpha_{\sigma}^{2\nu/(1+\nu)}}{\bar{\sigma}_{in}^{-(1-\nu)/(1+\nu)} * \left(\alpha_{\sigma} \bar{\sigma}_n\right)^{n(1-\nu)[\bar{\sigma}_{in} - (1/\alpha_o)]/(1+\nu)}} = 1,37 \quad (27)$$

Then the local strains and stresses in the zero half-cycle, respectively, will be equal to (28), (29)

$$\bar{e}_{\max}^{(o)} = \bar{e}_{in} * k_e^{(o)} = 0,66 * 3,517 = 2,32 \quad (28)$$

$$\bar{\sigma}_{\max}^{(o)} = \bar{\sigma}_{in} * k_{\sigma}^{(o)} = 0,77 * 1,37 = 1,055 \quad (29)$$

The exponent $\nu(k)$, at $F(k)=1$ is calculated using the formula (30):

$$\nu(k) = \frac{\lg \bar{e}_{\max}^{(o)\nu}}{\lg \left[\bar{e}_{\max}^{(o)0,17} + \frac{A}{2} \left(\bar{e}_{\max}^{(o)} - 1 \right) * F(k) \right]} = 0,171 \quad (30)$$

Theoretical concentration factors for stress and strain intensities are determined as follows (31), (32)

$$\alpha_{\sigma i} = \frac{\bar{\sigma}_{i\max}}{\bar{\sigma}_{in}} = \frac{1,83}{0,77} = 2,377 \quad (31)$$

$$\alpha_{ei} = \frac{\bar{e}_{i\max}}{\bar{e}_{in}} = \frac{1,82}{0,626} = 2,907 \quad (32)$$

The theoretical stress concentration factor is determined by the following formula (33):

$$\alpha_{\sigma} = \frac{\bar{e}_{i\max}}{\bar{e}_{in}} = \sqrt{\alpha_{\sigma i} * \alpha_{\sigma e}} = \sqrt{2,377 * 2,907} = 2,629 \quad (33)$$

The coefficient of increase in resistance to plastic deformation due to the volumetric nature of the stress state in the concentration zone is determined as (34)

$$I_{\max} = \sqrt{2 \left[\left(1 - \bar{\sigma}_{2\max} \right)^2 + \left(\bar{\sigma}_{2\max} - \bar{\sigma}_{3\max} \right)^2 + \left(\bar{\sigma}_{3\max} - 1 \right)^2 \right]} = 1,155 \quad (34)$$

Then the coefficient of reduction of the ultimate stress in the concentration zone will be equal to (35)

$$D_{e\max} = \frac{K_D}{I_{\max} * \left(1 + \bar{\sigma}_{2\max} + \bar{\sigma}_{3\max} \right)} = \frac{1,2}{1,155 * 1,5} = 0,693 \quad (35)$$

Therefore, the ultimate strain in the concentration zone is equal to (36)

$$\bar{e}_c = \bar{e}_k * D_{e\max} = 626 * 0,693 = 434 \quad (36)$$

The asymmetry coefficient of the nominal stresses will be equal to (37)

$$\bar{r}_{\sigma_{in}} = \bar{\sigma}_{in\min} / \bar{\sigma}_{in\max} = 0 / 0,77 = 0$$

The range of the nominal stresses in generalized coordinates ($\bar{S} - \bar{\varepsilon}$) is equal to (38)

$$\bar{S}_n = \frac{\bar{\sigma}_{in}}{\bar{S}_T^{(k)}} * (1 - r_{\sigma_{in}}) = \frac{0,77}{2} (1 - 0) = 0,385 \quad (38)$$

Then the strain concentration factor in the first half-cycle is equal to (39)

$$K_{\varepsilon}^{(1)} = \frac{\alpha_{\sigma}^{2/(1+\nu(k))} * \bar{S}_n^{(1-\nu(k))/(1+\nu(k))}}{\left(\alpha_{\sigma} * \bar{S}_n \right)^{\nu(1-\nu(k)) * [1 - (\bar{S}_n - 1 / \alpha_{\sigma})] / (1+\nu(k))}} = 2,65 \quad (39)$$

The maximum deformation in the first half-cycle will be (40)

$$\varepsilon_{\max}^{(1)} = \bar{\varepsilon}_n * K_{\varepsilon}^{(1)} = \left(0,385 * \frac{0,66}{0,77} \right) * 2,65 = 0,875 \quad (40)$$

The local deformation asymmetry coefficient is equal to (41)

$$r_{ek} = 1 - \frac{\bar{\varepsilon}_{\max}^{(1)}}{\bar{e}_{\max}^{(0)}} = 1 - \frac{0,875 * 2}{2,32} = 0,255 \quad (41)$$

The local deformation amplitude is determined by the formula (42)

$$\bar{e}_{a \max} = \frac{\bar{\varepsilon}_{\max}^{-(1)}}{2} = \frac{2 * 0,875}{2} = 0,875 \quad (42)$$

The fatigue limit of steel is equal to (43)

$$\bar{\sigma}_{-1} = K_{-1} * R_m = 0,4 * 545 = 218 \text{ MPa} \quad (43)$$

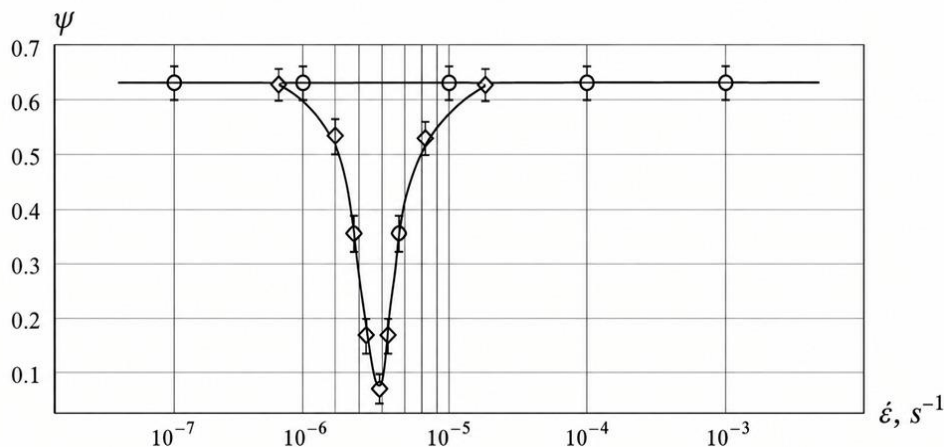
Calculation results

The number of loading cycles (N_T) before macrocrack formation during operation of a structure in a dry air environment under the rigid loading criterion is calculated using the Coffin-Manson calculation equation as follows

$$N_T = \left[\frac{1}{4} \left(\frac{\bar{e}_c}{\bar{e} \frac{\sigma_{-1}}{e_T E \left(1 + \frac{\sigma_{-1}}{R_m} \frac{1+r_{ek}}{1-r_{ek}} \right)}_{amax}} \right)^{1/m_p} \right] \\ = \left[\frac{1}{4} \left(\frac{434}{0,875 - \frac{218}{348(1+0,4*1,685)}} - 1,685 \right)^{1/0,5} \right] = 72 \text{ 630 cycle} \quad (44)$$

Methodology and results of experimental tests

Experimental test methodology and results. The material's ductility characteristics, which are included in the standard calculation equations, have a significant impact on the calculation results. Therefore, it was important to experimentally determine the effect of high-temperature water operating parameters on the plastic properties of steel. When testing the samples, the tensile method was used with different constant low strain rates in the range of values from 10^{-6} s^{-1} to 10^{-2} s^{-1} , and the following dependences of the steel ductility on the strain rate were obtained, shown in Figure 5. Each experimental point ψ_{exp}^T in Figure 5 corresponds to the average value of two or three tested samples.



● – data obtained in air; ◆ – data obtained in distilled water.

Figure 5 – Variation in the ductility of 10GN2MFA grade steel as a function of strain rate. [Author's material]

The experimentally obtained pattern of change in the ductility of the material in high-temperature water depending on the strain rate, shown in Figure 5, is analytically described by the following relationship (45):

$$\psi_{exp}^T = \psi_{std}^T \left[1 - \alpha \lg \frac{\dot{\varepsilon}_{std}}{\dot{\varepsilon}} - \beta \frac{1}{e^{\left(\frac{\dot{\varepsilon}_{cr} - \dot{\varepsilon}}{\gamma \dot{\varepsilon}_{cr}} \right)^2}} \right] \quad (45)$$

where ψ_{exp}^T - the steel ductility characteristic corresponding to the experimental strain rate $\dot{\varepsilon}$;

ψ_{std}^T - the steel ductility characteristic obtained in air testing using standard methods;

$\dot{\varepsilon}_{std}$ - the strain rate using standard testing methods;

$\dot{\varepsilon}_{cr}$ - the critical strain rate at which the maximum reduction in steel ductility is observed;

α, β, γ - coefficients determined experimentally.

The coefficients $\alpha = 0,013$, $\beta = 0,891$, $\gamma = 0,45$, characterizing changes in the material's strain capacity depending on the strain rate in water at high temperature and pressure, were determined from an experimental study.

For a strain rate equal to $\dot{\varepsilon}_{cr} = 10^{-6} s^{-1}$ in distilled water, the steel ductility is (46)

$$\psi_{exp}^T = \psi^T \left[1 - \alpha \lg \frac{\dot{\varepsilon}_{std}}{\dot{\varepsilon}_{cr}} - \beta \frac{1}{e^{\left(\frac{\dot{\varepsilon}_{cr} - \dot{\varepsilon}}{\gamma \dot{\varepsilon}_{cr}} \right)^2}} \right] = 0,67 \left[1 - 0,013 \lg \frac{10^{-2}}{10^{-6}} - \frac{0,891}{e^{\left(\frac{10^{-6} - 10^{-2}}{0,45 * 10^{-6}} \right)^2}} \right] = 0,0635 \quad (46)$$

The experimental data obtained by the authors of this paper on 10GN2MFA grade steel are compared with data obtained by other researchers [9].

The result of the ductility of steel in high-temperature water, obtained by calculation $\psi_{exp}^T = 0,0635$ and the data obtained by the authors from the experiment $\psi_{exp}^T = 0,045$, shown in Figure 5, correlate satisfactorily with the results of experimental tests given in [9] $\psi_{exp}^T = 0,1$, (curve 2, Figure 8, p. 59, Figure 9, p. 60). This paper presents the results of testing high-alloy heat-resistant steel 10GN2MFA under high-temperature corrosive environment conditions (typical for water-cooled nuclear reactors), which show a significant decrease in fatigue resistance due to the development of delayed strain corrosion cracking.

The number of loading cycles N_{exp}^T , corresponding to the critical strain rate $\dot{\varepsilon}_{cr} = 10^{-6} s^{-1}$ and characterizing the durability of the material before the formation of a macrocrack in a distilled water environment at a temperature of 280 °C and high pressure is determined by a similar formula (47):

$$N_{exp}^T = \left[\frac{1}{4} \left(\frac{\bar{e}_{ck}}{\bar{e}^{\frac{\sigma_{-1}}{e_T E \left(1 + \frac{\sigma_{-1}}{R_m} \frac{1+r_{\bar{e}_k}}{1-r_{\bar{e}_k}} \right)_{amax}} \frac{1+r_{\bar{e}_k}}{1-r_{\bar{e}_k}}} \right)}} \right)^{1/m_p} \right] = \left[\frac{1}{4} \left(\frac{25,4}{0,875 - \frac{218}{348(1+0,4*1,685)}} - 1,685 \right)^{1/0,5} \right] = 4458 \text{ cycle} \quad (47)$$

where, $\bar{e}_{ck}$ - the destructive relative strain for the vessel material in an environment of high parameters in the concentration zone is defined as (48),

$$\bar{e}_{ck} = \bar{e}_k * D_{e_{max}} = 37,3 * 0,693 = 25,4 \quad (48)$$

The maximum relative strain in water of high parameters is determined (49)

$$\bar{e}_k = \frac{1}{e_T} \ln \frac{1}{1 - \psi_{exp}^T} = \frac{0,065}{0,00177} = 37,3; \quad (49)$$

where, ψ_{exp}^T - the relative narrowing of the vessel material sample cross-section determined by experimental tests of a cylindrical shape 10GN2MFA grade steel samples of a solid cross section with a diameter of 10 mm in a chamber with distilled water at a temperature of 280°C at the strain rates $\dot{\varepsilon}_{std} = 10^{-2} s^{-1}$ and $\dot{\varepsilon}_{cr} = 10^{-6} s^{-1}$.

Using an analytical relationship between the change in ductility and the strain rate associated with changes in the equipment operating mode during a single cycle, the total cycle time t and the fraction of time during which the strain rate will pass through the critical strain-rate range t_{cr} can be determined. Then the critical strain-rate influence coefficient can be expressed as follows:

$$K_{\dot{\varepsilon}_{cr}} = \frac{t_{cr}}{t} \quad (50)$$

As Figure 5 shows, the fraction of time during which the vessel body strain rate will be in the critical strain-rate range is

$$K_{\dot{\varepsilon}_{cr}} = \frac{t_{cr}}{t} = \frac{1}{5} = 0,2 \quad (51)$$

Using the linear summation method, the overall design life of the vessel is the sum of the service life under load in the critical strain-rate range and the service life under load outside the critical strain-rate range (52):

$$N_{tot} = N_{exp}^T * K_{\dot{\varepsilon}_{cr}} + N_T (1 - K_{\dot{\varepsilon}_{cr}}) = 4458 * 0,2 + 72630 * 0,8 = 58996 \text{ cycles.} \quad (52)$$

Discussion

Laboratory experimental tests revealed that when testing a sample with a relative strain rate equal to $\dot{\varepsilon}_{cr} = 10^{-6} s^{-1}$, which is called the critical strain rate, in a high-temperature corrosive environment, the ductility characteristic of the studied 10GN2MFA grade steel has a minimum value of $\psi_{exp}^T = 0,0635$.

The experimental fatigue-life data as a function of the cyclic strain amplitude of the test sample, obtained in distilled water at pH 7 and a temperature of 280°C, are presented in Table 2.

Table 2 - Experimental fatigue-life data as a function of cyclic strain amplitude in a corrosive environment. [Author's material]

$\varepsilon_{a,max}$	1.6	1.4	1.2	0.8	0.6	0.45
N	450	820	1200	4200	5400	6800

The cyclic loading frequency was $f = 1$ cycle/min, corresponding to the specified strain rate $\dot{\varepsilon} = 10^{-3} s^{-1}$. As shown by the experimental results, at $\varepsilon_{a, max} = 0.8$, the experimental fatigue life, $N = 4200$ cycles, is in good agreement with the calculated value, $N_{(cs)} = 4458$ cycles. The slight discrepancy is attributable to the difference in loading conditions: the actual loading is pulsating, whereas symmetric cyclic loading was applied in the experiment.

The reduction in durability in a corrosive environment at the strain rate of the vessel body material $\dot{\varepsilon}_{std} = 10^{-2} s^{-1}$, compared to the durability in air, is approximately 5%.

In the case of a variable strain rate, changing from minimum $\dot{\varepsilon}_{cr} = 10^{-6} s^{-1}$ to maximum $\dot{\varepsilon}_{exp} = 10^{-2} s^{-1}$ through the critical strain rate zone, with a minimum ductility of $\psi_{exp}^T = 0,0635$, the critical strain rate fraction was $K_{\dot{\varepsilon}_{cr}} = 0,2$. The experimental results obtained from tests conducted in dry air at a temperature of 280°C are presented in Table 3. At a cyclic strain amplitude of $\varepsilon_{a, max} = 0.875$, the number of cycles to failure, determined from the approximated curve based on the experimental

data presented in Table 3, was 75,000 cycles. In comparison, the fatigue life calculated using the proposed method for distilled water was 58,996 cycles. Thus, the calculated reduction in fatigue life in the corrosive environment relative to the experimentally determined fatigue life in dry air was 21.3%. Therefore, the reduction in fatigue life may be taken as approximately 20%.

Table 3 - Experimental fatigue-life data as a function of cyclic strain amplitude in dry air. [Author's material]

$\varepsilon_{a,max}$	1.6	1.4	1.0	0.8	0.6
N	20000	40000	46000	84000	160000

This result shows that if the low-cycle loading frequency and the stress-strain cycle shape are such that the strain rate approaches the critical strain-rate, i.e., the coefficient value $K_{\varepsilon_{cr}}$ is greater, then the durability reduction will further increase.

Conducting experimental testing of steel samples in high-parameter environments is complex and time-consuming. Therefore, the experimental testing was limited to 2-3 samples per point.

Therefore, to obtain a full spectrum and build an experimental data base, further research is required on the properties of steel in expanded environmental conditions (the presence of impurities, dissolved oxygen, boric acid, and other substances in water).

4 CONCLUSIONS

1. Based on the experimental study and calculations using standardized computational models based on deformation failure criteria, this article demonstrates that, in addition to the strength characteristics of the material, its durability under low-cycle fatigue, both in air and in a corrosive environment, was significantly affected by its ductility.

2. A relationship between low strain rates and the ductility of the material during strain in the low-cycle loading region was established.

3. The existence of a critical strain rate for this steel in high-temperature water was established, at which the ductility of the material decreased by an order of magnitude.

4. The significant reduction in the estimated durability of the vessel material before the formation of the main crack in the high-temperature aqueous environment was noted.

5. The increased negative effect of high-temperature water on durability was demonstrated at strain rates close to the critical strain rate for this steel.

6. The analytical description of the relationship between steel ductility and low strain rates was proposed. The range of critical strain rates was determined.

7. The algorithm for calculating the static and cyclic strain characteristics in the stress concentration zone and the durability of the structural element at the stage of main crack formation under low-cycle loading was presented.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

ARTIFICIAL INTELLIGENCE STATEMENT

During the preparation of this manuscript, the authors used the artificial intelligence tool ChatGPT solely for editorial assistance, including improving wording and checking grammar, spelling, and punctuation. All scientific ideas, interpretations, analyses, and conclusions are the responsibility of the authors, who take full responsibility for the content of the article.

AUTHOR CONTRIBUTIONS

Khassen Abshenov - Conceptualization, formulation of the research objectives, coordination of the research team, development of the research concept and overall methodology for the calculations and experimental investigations, supervision, analysis and interpretation of the results, writing and editing of the manuscript.

Batyrbek Arapov - Development of the testing facility, design and calculation of the test chamber and load-bearing components, development of the fatigue life calculation methodology, mathematical modeling, interpretation of the results, manuscript editing.

Alpysbai Ainabekov - Methodology, validation of the computational model, scientific consultation, analysis of the results, manuscript editing.

Mirziyod Mirsaidov - Scientific consultation, analysis and interpretation of the results, discussion of the findings, manuscript editing.

Omarbek Alibekov - Participation in the computational analysis, data processing, preparation of figures and graphical materials, participation in manuscript preparation.

Svetlana Buganova - Participation in the experimental investigations, processing and analysis of the experimental data, participation in manuscript preparation and editing.

Bakdaulet Zhailybek - Fabrication, assembly, and commissioning of the testing facility; installation of auxiliary equipment (high-pressure pump, receiver, gas supply system, and pipelines); commissioning of the experimental setup; ensuring its reliable operation; participation in the experimental investigations.

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