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CONTRIBUTION OF ENDOGENOUS TITANIUM NITRIDE INCLUSIONS TO THE DEVELOPMENT OF LOCAL STRESSES IN 08Kh18N10T STEEL

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The effect of the endogenous titanium nitride inclusions on local stresses in the matrix of 08Kh18N10T austenitic steel was studied. For spherical inclusions coherent with the matrix, local stresses were obtained. Local stresses exceeded the minimum yield strength. The trend in stress variation with inclusion size and shape was determined. It has been demonstrated that the magnitude of stresses escalates with the enlargement of TiN inclusion size and the transition of their morphology from spherical to cubic forms. Additionally, the characteristics of matrix failure in the vicinity of clusters of endogenous TiN inclusions are analyzed.

INTRODUCTION

During the operation of heat exchange equipment within aggressive aqueous environments containing active constituents, the material of the heat transfer surfaces undergoes degradation resulting from both physical and chemical interactions at the interface between the metal and the medium. The presence of operational defects on the external surface of heat exchange tubes situated on the secondary circuit side can precipitate metal failure [1, 2]. Such failures are predominantly attributed to corrosion-induced deterioration of the steel components.

The mechanisms underlying corrosion-induced deterioration have been extensively characterized [3]. Among these, the most thoroughly examined phenomena include stress-corrosion cracking, corrosion fatigue, fretting corrosion, hydrogen embrittlement, and corrosive wear. These processes exert a substantial influence on the structural integrity and longevity of steel components under operational conditions, thereby critically affecting the economic viability and safety of nuclear power plant operations.

Operational experience at Ukrainian nuclear power plants has demonstrated that PGV-1000/PGV-1000M steam generator (SG) heat exchangers, when subjected to prolonged water flow conditions, tend to experience deterioration in their mechanical properties, predominantly due to stress corrosion cracking [4]. Such corrosion processes can significantly deplete the technological reserve of the heat exchanger bundles prior to the decommissioning of the SG, which occurs at the end of its designated service life. Consequently, this degradation compromises the operational integrity of the entire SG, necessitating its replacement and ultimately resulting in the shutdown of the associated power unit.

Since its initial emergence, the issue has been extensively addressed through the publication of numerous scholarly articles, the execution of a diverse array of research and design initiatives, and the modernization of heat-exchange tube control systems as well as enhancements to the water chemistry of secondary circuits [5, 6]. Despite these efforts, the challenge of stress corrosion cracking continues to persist unresolved. The primary difficulty in predicting the initiation and progression of stress corrosion cracking stems from the current absence of a comprehensive mathematical model that encapsulates the underlying mechanisms within a unified framework. Such a model would need to account for the combined and synergistic effects of individual factors, which can collectively influence the development and behavior of stress corrosion cracking processes. These factors encompass structural imperfections within the material, phase composition, the hydrodynamic properties of heat exchangers, and the thermodynamic conditions of the surrounding environment, all of which may fluctuate during the operational lifespan of the equipment. Among these, endogenous nonmetallic inclusions represent a notable factor; these inclusions are particles generated intrinsically within steel as a consequence of internal chemical reactions or processes, rather than originating from external contamination sources. These phenomena predominantly originate from the interactions between elements dissolved within the molten material and gaseous constituents such as oxygen, sulfur, and nitrogen. The presence of inclusions within steel introduces stress concentrators, which significantly influence the material's mechanical properties. The extent and distribution of stress concentration at the interface between inclusions and the matrix are governed by multiple factors, including the coherence between phases, the coefficient of thermal expansion, as well as the shape and size of the inclusions.

The objective of this study is to assess the impact of endogenous titanium nitride inclusions on the local stress distribution within the matrix of austenitic steel grade 08Kh18N10T.

1. MATERIALS AND METHODS

The subject of this research was corrosion-resistant steel 08Kh18N10T, an austenitic alloy, which is employed in the fabrication of heat exchange tubes within the SG bundle of the PGV-1000/PGV-1000M type power units used in WWER-1000 nuclear power plants in Ukraine.

The microstructural characteristics of the steel were examined employing metallographic techniques, optical microscopy, and digital imaging. To ascertain the elemental composition and phase identification, a JEOL JSM-7001F scanning electron microscope (SEM), equipped with a Schottky cathode and equipped with X-ray fluorescence analysis capabilities, was utilized.

The analysis of operational defects was conducted utilizing eddy current testing data derived from the material of the SG heat exchanger tubes [7, 8].

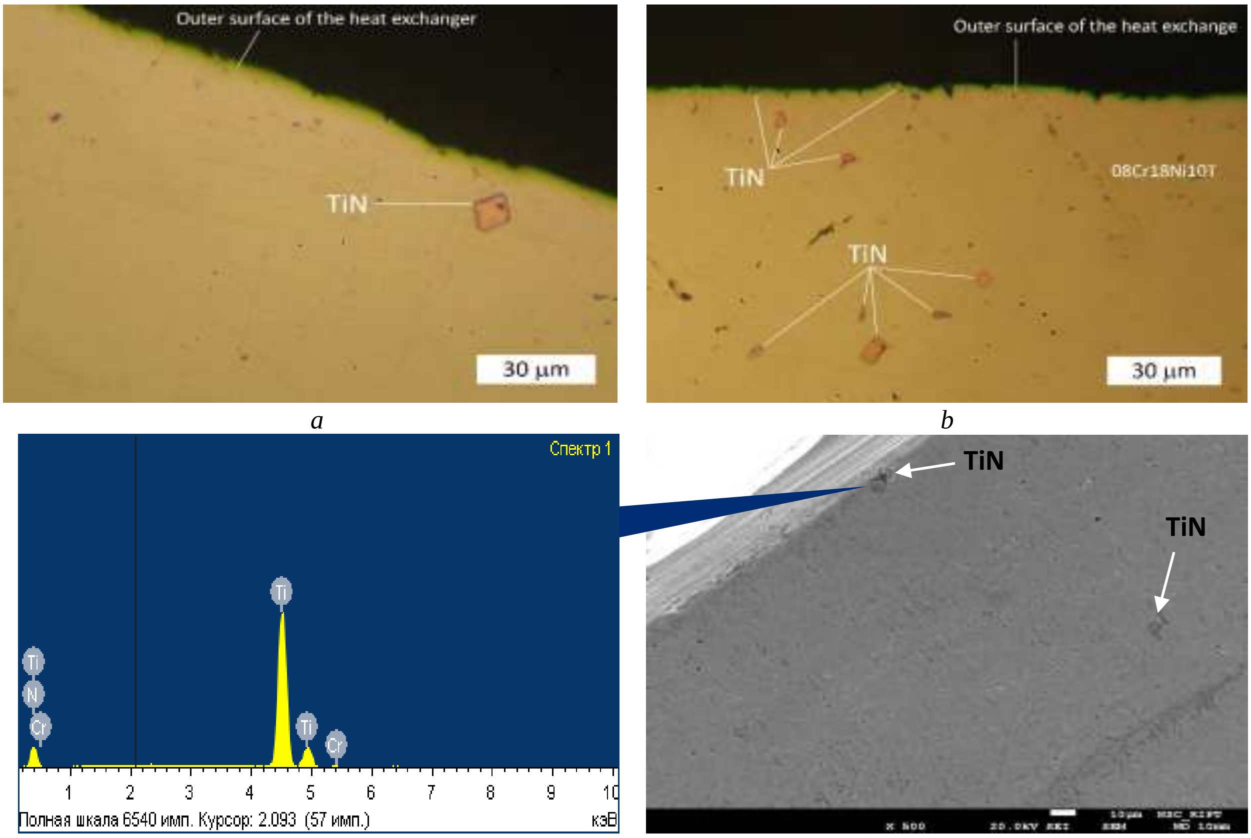
For the purpose of stress evaluation, a spherical inclusion model served as the foundational framework [10–12].

2. RESULTS AND DISCUSSION

Metallographic analysis of specimens extracted from heat exchange tubes demonstrated that titanium nitride inclusions predominantly exhibit cubic or rectangular morphologies, occasionally forming fragments with intricate geometries. Fig. 1 presents representative micrographs of these inclusions. Typically, the inclusions do not exceed 3…7 µm in their maximum dimension. The mean size of inclusions with regular shapes is approximately 5 µm (see Fig. 1,a).

The spatial distribution of TiN inclusions within the volume exhibits heterogeneity. Both solitary inclusions and agglomerates are observed throughout the material (see Fig. 1,b). In particular, regions proximate to the outer surface and the central segment of the pipe wall display localized clustering of TiN inclusions, wherein the inter-inclusion distances are approximately proportional to their respective dimensions (see Fig. 1,d). Titanium nitride clusters are formed either via the aggregation of multiple discrete inclusions exhibiting a range of sizes and geometrical shapes or through the alignment of several inclusions arranged in a linear, row-like configuration.

Based on metallographic analyses [9], titanium nitride inclusions within austenitic heat exchanger steel predominantly exhibit corner-shaped faceting and are characterized by cubic or parallelepipedal geometries. These inclusions generally do not exceed 3…7 µm in their maximum dimension. The mean size of inclusions with a regular, well-defined morphology is approximately 5 µm.



a *b*

c *d*

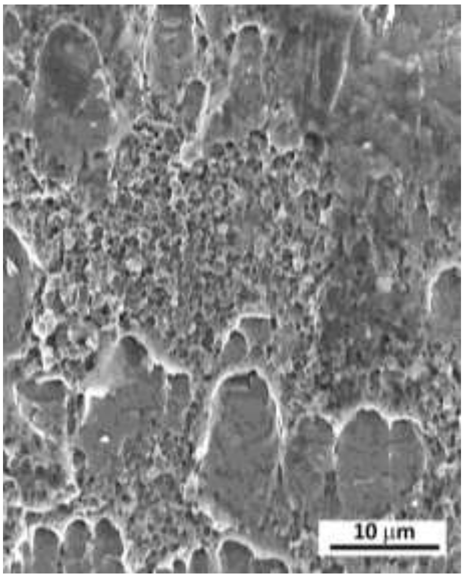
Fig. 1. TiN inclusions in 08Kh18N10T steel: square TiN (optical microscopy) (a, b); X-ray fluorescence analysis of the inclusion TiN (c); inclusion on the outer surface of a heat exchanger (SEM) (d)

The observed pattern appears to be attributable to the manufacturing process of the heat exchanger, specifically the rolling procedure. This process induces localized non-uniform deformation, which is associated with the complex stress distribution surrounding inclusions.

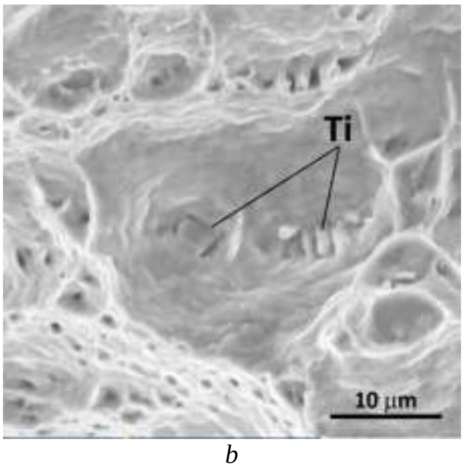
Subsequently, scanning electron microscopy images of the fracture surfaces of 08Kh18N10T steel specimens were acquired following mechanical testing. The fracture morphology is characterized as heterogeneous and composite (Fig. 2,a), comprising alternating microregions where both ductile and brittle fracture mechanisms coexist. Specific regions of the fracture surface display zones of diminutive, nearly planar pits less than 1 µm in diameter, which constitute a honeycomb-like relief. This feature is indicative of predominantly brittle intragranular fracture.

Conversely, larger, elongated pits with fibrous margins suggest fracture through a ductile mode, occurring perpendicular to the principal tensile stress applied during testing.

Fig. 2,b shows a fracture surface section containing TiN inclusions.



a



b

Fig. 2. Fracture surfaces of 08Kh18N10T steel: morphology (a), surface section containing TiN inclusions (b)

It is important to observe that individual inclusions may be positioned on the external surface of the material, which is in direct contact with the aggressive coolant medium. Such localization undermines the homogeneity of the pipe's outer surface, thereby promoting the deterioration of the passivation layer.

To estimate the magnitude of the stress, a spherical inclusion model was employed as the foundational framework, owing to its relative simplicity. The mathematical representation of a cubic inclusion in three-dimensional space, along with the corresponding solution to such a problem – considering numerous influencing factors – is notably complex.

For the purposes of calculation, it was assumed that the TiN inclusion is spherical with a radius of 2.5 μm and maintains coherency with the surrounding steel matrix. The issue of inclusion-matrix coherency is inherently complex, as it depends on a multitude of factors, and warrants a separate, detailed investigation.

Determining the stresses at the inclusion-matrix interface theoretically, taking all factors into account, is quite difficult. Therefore, certain assumptions and simplifications are used.

To estimate the stress values, a formula derived from references [10, 11, 12] was employed. This formula is designed for the determination of elastic stresses in the vicinity of spherical inclusions. Additionally, data pertaining to the mechanical properties of titanium nitride inclusions and the austenitic steel matrix 08Kh18N10T were incorporated into the analysis.

The stress level will be determined by the degree of difference in the properties of the inclusion and the matrix. The data presented in Table were used for the calculations.

Analytical calculations have demonstrated that, under specified conditions, the stress concentrations within the matrix of 08Kh18N10T steel surrounding a spherical titanium nitride inclusion can attain a magnitude of 200 MPa. The calculated stress level for this steel surpasses the minimum permissible yield strength threshold ($R_{p0.2} \geq 172$ MPa) at a temperature of +300 °C, in accordance with regulatory standards [14]. Typically, the actual mechanical strength properties of austenitic 08Kh18N10T steel in practical applications tend to exceed the normative values.

The findings from the mechanical testing conducted on samples exhibiting operational defects [15] substantiate this assertion. Specifically, the yield strength of steel heat exchange pipes at +350 °C was observed to range between $R_{p0.2}$ = 320 and 360 MPa, marginally exceeding the standard values established in reference [16].

Regarding the impact of the size of spherical TiN inclusions, research documented in reference [17], which employed mathematical modeling alongside mechanical fatigue testing on structural alloy steel 20CrMnTi (analogous to 18KhGT), demonstrates a correlation between inclusion radius and stress levels. Specifically, an increase in the radius of TiN inclusions from 1.5 to 10 μm corresponds to an increase in stress from 1133 to 1185 MPa.

Initial data for calculations [13, 14]

ΔT	08X18H10T				TiN			
℃	ν_m	E_m, Pa	R_m, m	α_m, C^{-1}	ν_{inc}	E_{inc}, Pa	R_{inc}, m	α_{inc}, C^{-1}
300	0.29	$1.80\cdot10^{11}$	$2.5\cdot10^{-6}$	$17.2\cdot10^{-6}$	0.192	$3.20\cdot10^{11}$	$2.5\cdot10^{-6}$	$9.4\cdot10^{-6}$

E_{inc}, E_m – modulus of elasticity of inclusion and steel matrix at 300 °C; R_{inc}, R_m – radius of inclusion and matrix area associated with inclusion; α_{inc}, α_m – coefficients of linear thermal expansion at 300 °C; ν_{inc}, ν_m – Poisson's ratio; ΔT – change in temperature; d^3 – coefficient, which is equal to 0.0005 [12].

$$\sigma = \frac{P}{1-d^3}\left(\frac{1}{2}\frac{R_{inc}^3}{R_m^3} - d^3\right),$$

where $$P = \frac{(\alpha_m - \alpha_{inc})\Delta T}{\frac{\frac{1}{2}\left(1+\nu_m+(1-2\nu_m)d^3\right)}{E_m\left(1-d^3\right)} + \frac{1-2\nu_{inc}}{E_{inc}}}.$$

The researchers cited in references [17, 18] conducted investigations that elucidated the impact of titanium nitride inclusion morphology on the mechanical durability of low-carbon steel. Their findings indicated that, for inclusions of equivalent spherical and cubic geometries, the stress concentrations within the steel matrix could surpass the material's yield strength. Furthermore, an increase in the size of cubic inclusions was associated with a heightened propensity for fatigue failure, a relationship substantiated through mechanical fatigue testing.

Mathematical modeling employing the finite element method [17] demonstrated that the stress distribution within the matrix is augmented in the presence of cubic inclusions. Furthermore, the analysis revealed that stress concentration predominantly localizes in the vicinity of the cubic TiN inclusion (Fig. 3).

Previously, the author of [19] obtained the dependence of the stress concentration coefficient on the inclusion geometry, as well as on the ratio of the Young's moduli of the inclusion and matrix. Obviously, the stress concentration increases if $E_{inc} < E_m$, then the ratio of these moduli will be $(E_{inc}/E_m) < 1$.

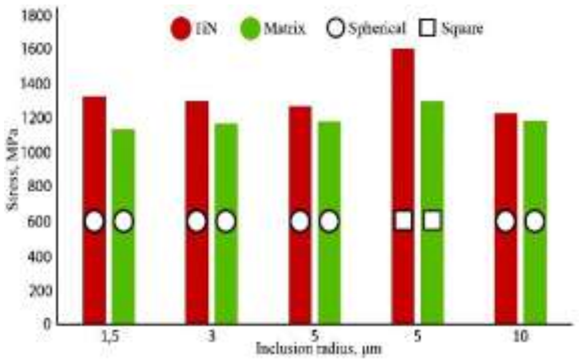


Fig. 3. Dependence of stresses in the matrix on the size and shape of inclusions

It should be kept in mind when the Young's modulus of the inclusions was greater than that of the steel matrix, the strain force of the matrix was greater during the fatigue loading, resulting in stress concentrations on the sides of the inclusions. Taking TiN as an example, under extreme fatigue conditions, the inclusions reached their critical fatigue limits earlier than the steel matrix. As the stress concentrations increased, the TiN inclusions broke before the steel matrix, and such cracks subsequently extended into the steel matrix.

It can be postulated that, for 08Kh18N10T steel, the trend of increasing stress concentration within the matrix surrounding titanium nitride (TiN) inclusions will continue. This raises pertinent questions regarding the influence of inclusion morphology on the stress distribution within the matrix. To investigate the geometric effects of TiN inclusions on stress concentration, it was essential to standardize the inclusion sizes across different shapes.

Consequently, simulation models were constructed with the same characteristic dimensions: the circular TiN inclusions had a diameter of 5 µm, while the square TiN inclusions possessed a side length of 5 µm.

Under these comparable size conditions, the regions of elevated stress and reduced fatigue life associated with the square TiN inclusions were more extensive than those observed around the circular inclusions.

The Ti inclusions characterized by large particle size and pronounced angular morphology inevitably originated within the molten steel. These inclusions proved to be challenging to eliminate during subsequent processing, thereby contributing to a decline in the steel's toughness and fatigue resistance. The presence of sizable, hard, and brittle non-metallic oxide inclusions significantly influenced the fatigue properties of the material. Comparative analyses of fatigue crack initiation mechanisms under rotational and bending stresses in analogous rigid materials indicated that internal defects – primarily those induced by inclusions – could serve as direct precursors to fatigue crack formation.

In our case, the obtained ratio of the elastic modulus for the TiN inclusion and the steel matrix has an inverse value $(E_{inc}/E_m) > 1$. This indicates that stresses will be concentrated within the inclusion itself. This also leads to the development of microcracks in the inclusion. As the stress concentration increases, the TiN inclusions fail before the steel, and the cracks propagate into the steel matrix [17].

In the present study, the ratio of the elastic modulus for the TiN inclusion relative to the steel matrix (E_{inc}/E_m) exceeds unity, indicating an inverse relationship. This suggests that stress concentration predominantly occurs within the inclusion itself. Consequently, this localized stress accumulation facilitates the initiation of microcracks within the TiN particles. As the stress concentration intensifies, the inclusions are more susceptible to premature failure compared to the surrounding steel matrix, thereby promoting crack propagation into the matrix material [17].

It is important to highlight that the mechanical properties, specifically the strength and ductility, of 08Kh18N10T and 20CrMnTi steels exhibit notable differences: the heat exchanger-grade steel demonstrates greater ductility but comparatively reduced strength. Owing to its enhanced ductility and other associated attributes, 08Kh18N10T steel may present marginal variations in strain distribution, microstrain magnitudes, and stress concentration patterns in the vicinity of inclusions.

CONCLUSIONS

Calculations show that for spherical inclusions TiN, provided they are coherent with the steel matrix, local stresses around them in austenitic heat exchanger steel exceed the minimum yield strength.

Based on experimental findings, comprehensive literature review, and computational modeling, it is postulated that the stress levels within the matrix of

08Kh18N10T steel escalate concomitantly with the growth in size of TiN inclusions, irrespective of their morphology – whether spherical or cubic.

Mathematical modeling, in conjunction with mechanical fatigue testing, indicates that the cubic morphology of TiN inclusions amplifies both the extent and intensity of localized stresses within the steel matrix. This phenomenon potentially facilitates heterogeneous local deformation and leads to non-uniform reinforcement of the steel matrix.

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ВНЕСОК ЕНДОГЕННИХ ВКЛЮЧЕНЬ НІТРИДУ ТИТАНУ В РОЗВИТОК ЛОКАЛЬНИХ НАПРУЖЕНЬ У СТАЛІ 08Х18Н10Т

Є.О. Крайнюк

Досліджено вплив ендогенних включень нітриду титану на локальні напруження в матриці сталі аустенітного класу 08Х18Н10Т. Для включень сферичної форми за умов їх когерентності з матрицею отримано локальні напруження, значення котрих вище мінімальних значень границі плинності. Визначена тенденція щодо зміни напружень від розміру та форми включень. Показано, що зі збільшенням розміру включень TiN, а також змінення їх форми зі сферичної на кубічну напруження будуть зростати. Розглянуто характер руйнування матриці навколо групи ендогенних включень TiN.