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Structural and mechanical defects of materials of offshore and onshore main gas pipelines after long-term operation

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Abstract: The study has established the main regularities of a fatigue failure of offshore gas steel pipes installed using S-lay and J-lay methods. We have numerically analyzed the influence of preliminary deformation on the fatigue life of 09Mn2Si steel at different amplitudes of cyclic loading. The results have revealed the regularities of formation and development of a fatigue crack in 17Mn1Si steel after 40 years of underground operation. The quantitative analysis describes the regularities of occurrence and growth of fatigue cracks in the presence of a stress concentration.

Keywords: defects of materials; fracture; damage; S-lay and J-lay methods

1 Introduction

The safe operation of onshore and offshore gas pipelines depends both on their proper design and installation; as well as on adequate operation conditions affecting the degree of pipe material degradation [1, 2]. For instance, offshore pipeline installation can lead to a preliminary deformation of pipes. This leads to structural changes of the material, which can reduce its performance [3]. Before the installation of a pipe, its wall material is analyzed by the evaluation of a stress-strained state taking into account the supposed installation methods. The evaluation results include formulated operation sheet, reports and acceptable level of defects in field circumferential weld joints of the pipe. Moreover, in addition to the installation damage of a pipe its life depends on a cyclic mechanical loading. The combined effect of the said two factors on the life of pipelines is disregarded by engineers and requires further investigation [4]. Therefore, the study of material behavior and discovery of micromechanisms describing the cyclic deformation and failure under the conditions of predeformation, which simulates the processes occurring during pipe installation, is a topical scientific and engineering challenge.

For onshore pipelines, one shall take into account the pipe material degradation due to the deformation caused by the subsidence of ground and hydrogen adsorption (hydrogenation). Currently, these effects are insufficiently examined, since they are individual for different climate zones. However, the establishment of generalized regularities of such processes will enable the forehanded diagnosis of pipe condition, assignment of safe operation life and substantial extension of pipeline life. Such approaches are also very useful for calculating pipeline life, reviewing the remaining life and choosing the criteria for the assessment of structural and mechanical damage [5, 6].

The aim of this work was to study the micromechanisms of fatigue failure of steel offshore pipeline after deformation that simulate different pipe installation methods. The work also studies the regularities of fatigue crack growth in the pipe of an onshore gas pipeline during long operation period.

2 Methods

Offshore gas pipeline material. Our study involved the testing of cylindrical 09Mn2Si steel specimens with the diameter of five millimeters. The specimens were cut from a 16-millimeter wall of a seamless hot-deformed pipe having the diameter of 426 millimeters, Figure 1 a, b.

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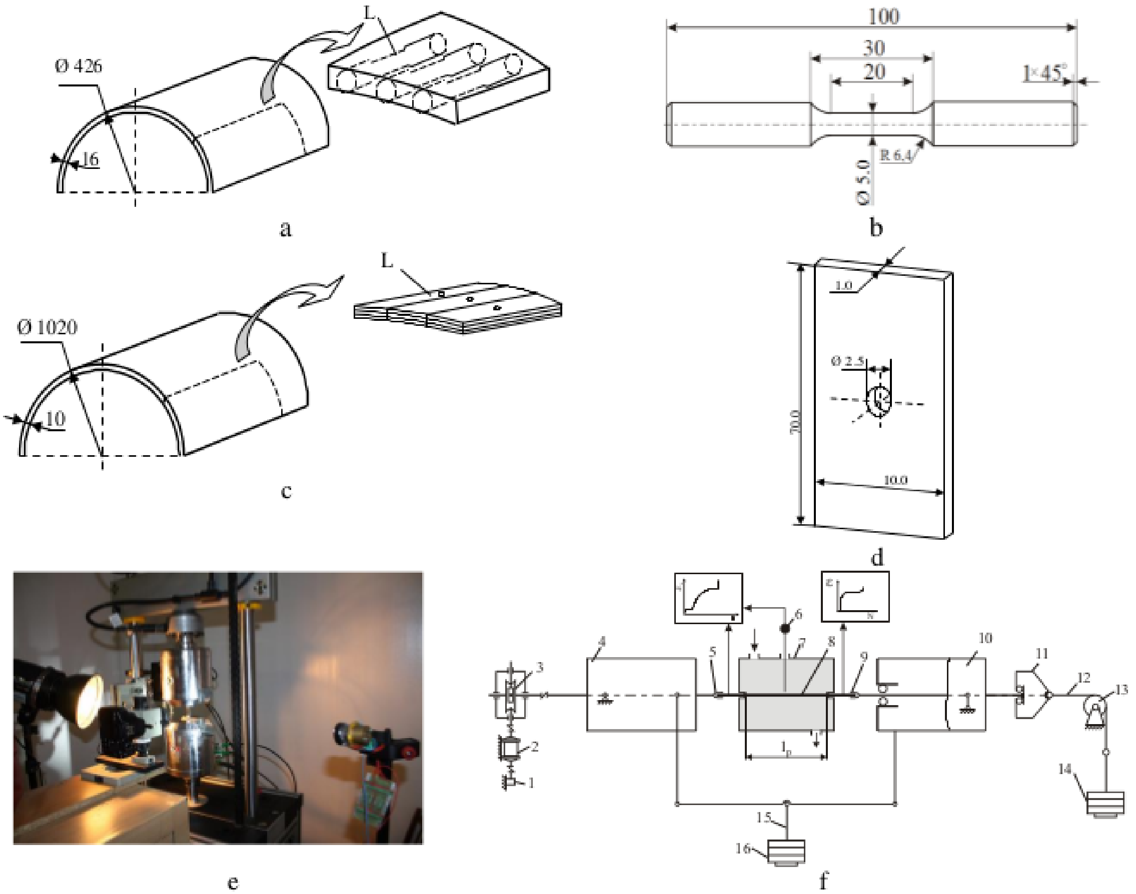

Figure 1: Scheme of cutting specimens from the offshore (a) and onshore (c) main gas pipelines for fatigue testing (b, d), and a photo of cyclic tension tests (e) and scheme of testing device MB-1K (f): 1 cycle counter; 2 electric motor; 3 worm gear; 4 leading drum; 5, 9 clamp; 6 reference electrode; 7 removable operating chamber; 8 experimental sample; 10 driven drum; 11 movement converter; 12 wire; 13 roller; 14, 16 variable load; 15 craving.

Table 1: Chemical composition of offshore pipeline steel.

Chemical composition of 09Mn2Si steel [%]								
C	Si	Mn	S	P	Nb	Cr	Ti	V
0.092	0.32	1.31	0.031	0.022	<0.004	0.25	0.027	0.0025

Table 2: Chemical composition of onshore pipeline steel.

Chemical composition of 17Mn1Si steel [%]								
C	Si	Mn	Ni	S	P	C	N	Cu
0.15–0.2	0.4–0.6	1.15–1.6	up to 0.3	up to 0.04	up to 0.035	up to 0.3	up to 0.008	up to 0.3

Table 3: Cyclic durability of 17Mn1Si steel specimens after 40 years of operation.

Durability of material	Location of sampling		
	Outer layer	Core	Inner layer
Crack formation (a = 0.1 mm) N_i, cycles	34090	44307	47705
Boundary state, N_f, cycles	83289	63551	61972

The gauge length of the specimens was 30.0 millimeters. The chemical composition of steel is presented in Table 1.

The specimens were used for simulating the installation of a pipeline by S-lay and J-lay methods [3]. The simulation of the deformation exposure was carried out using the model specimens subjected to stepwise loading. One-step increase or decrease of the load led to the change in nominal stress by $\Delta\sigma_{pr} = 20$ MPa. The simulation of the conditions of S-lay pipeline installation was performed by a single-cycle alternating loading of specimens. In the bending diagram, the stress is displayed as a loop of mechanical hysteresis consisting of two semi-cycles.

The first semi-cycle of specimen loading corresponded to J-lay pipeline installation method. The whole deformation process corresponded to S-lay method. Preoperational deformation (PD)–simulation of pipe installation was conducted solely in the air. The damage of insulation coating in the cycle of preoperational deformation was neglected. Fatigue tests of 09Mn2Si steel specimens were carried out by pure bending in seawater at the stress amplitudes $\sigma_a = 260$, 320 and 420 MPa. Frequency of cycling was 0.8 Hz.

The MB-1K setup provides loading of the specimen by the scheme of 4-poin bending during its rotation. The drive is provided from the motor through the worm gear and drums. In the process of testing, the experimental parameters were continuously recorded into the PC (the number of loading cycles and specimen deflection), Figure 1 f [7].

Onshore gas pipeline material. Flat specimens with the size of $70 \times 10 \times 1$ mm with a $\varnothing$2.5 mm central holes were cut from 1020 mm diameter pipe, Figure 1 c, d. Chemical composition of the pipe steel is presented in Table 2.

A stress concentrator was represented by a two-millimeter hole. The specimens were tested on cyclic tensile using BiSS UTM 150 servohydraulic testing machine. During the fatigue testing, the images of the specimens were captured by Canon 550D DSLR camera, Fig 1e. At least 3 specimens were tested under each test pattern. Then the data were averaged in accordance with the recommendations of standards. The statistical analysis and evaluation of dispersion were not performed, since the article is dedicated to phenomenology[1].

3 Experimental results

Onshore pipelines. The cyclic loading of the material leads to the generation of dissipative mesostructures and deformation of the material. The origin of a fatigue defect is the ultimate stage of the deformation of the material, when a global loss of shear stability takes place at the macro level, and the main fatigue crack starts to grow [8]. Obviously, the largest rate of the crack formation is demonstrated by the outer layer of the pipe at $N_i = 34,090$ cycles. In the core and inner layers of the pipe the amount of cycles before crack formation is practically equal and lies in a narrow range $44,307 \le N_i \le 47,705$ (Table 3).

The latest cracks formed in the outer layer, which is due to its significant hardening in the process of pipe fabrication. This effect is conditioned by the process of cold hardening and the specific texture of a layer. Consequently, this structural and mechanical feature expressed by the banded structure of ferrite and perlite grains elongated in the rolling direction allows inhibiting the growth of cracks across the texture of the material. This leads to increased cyclic durability as compared to specimens obtained from core and inner layers of the pipe [9].

The analysis of the curves expressing the growth of fatigue cracks allowed us to trace the distinction of its kinetics (Figure 2 a). Physical regularities are shown at the fractures of specimen (Figures 2 b–2 e) and will be analyzed below. The physical nature of the micromechanisms of all failed specimens of the onshore main gas pipeline is very similar. We shall point out that the fracture of a specimen is perpendicular to the tensile axis, and its deformation degree depends on the degree of the constraint of lateral deformation (along the front of a crack).

The degree of the constraint of lateral deformation depends on the crack length. When the length increases, the flat strain transforms into three-dimensional strain [10]. One shall account that in the areas of stress concentration and crack occurrence at nominal stress that does not exceed the yield stress, usually there is a cyclic elasto-plastic deformation of a material. Concurrently, the failure occurs as a result of its low-cycle fatigue. In this context we can outline several main stages of a fatigue failure (Figure 2 e):

- zone of crack formation starting at the surface of stress concentrator (I); the formed fatigue crack is oriented in perpendicular to the direction of force application. Its growth is stipulated by shear-rotation processes in grain conglomerates, which is reflected by the turns and displacements of the areas of the material between fatigue striations;

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- zone of stable cracking (II); the fracture surface is more rough. Orientation of fatigue striations is irregular. The direction of their propagation in some areas significantly deviates from the direction of the main crack growth. Their width varies, and the relief indicates the presence of significant local plastic strains and rupture of the material between adjacent sections of nonuniform propagation of the fatigue crack;
- zone of considerable plastic deformations and fracture (III); fatigue striations in this zone are alternated with the traces of ductile detachment of the material. It is confirmed by the decrease in their step (Figure 2). This also affects their shape, and almost all of them have a deformed front. Numeric values of the average step of fatigue striations along the specimen are shown in the Figure 3.

We studied the step of fatigue striations along the fracture front of a specimen (Figure 3). We shall outline that the kinetics of fatigue striations step change (at microlevel) differs from the kinetics of fatigue crack growth (at macrolevel), whose growth rate rises with the length increase. Thus, in this case the step of fatigue striations cannot be used for quantitative evaluation of the crack resistance of a material. Such physical anomalies indicate that the formation of fatigue striations were accompanied by other mechanisms, primarily ductile failure mechanisms. It is their influence on the morphology of the fracture that does not allow using the step of fatigue striations as a numerical parameter for estimating crack resistance of 17Mn1Si steel.

It is known that the fatigue crack tip propagates by the mechanism of shear and rotation. With an increase in its length, turning mechanisms of deformation becomes active in the plastic zone near the crack tip [11, 12]. With an increase in the crack length, the step of striations increases, as it was found for the 17Mn1Si steel. Thus, the process of fracture has a fatigue nature with clear-cut fatigue striations.

However, a change in the mechanism of fracture from purely fatigue to a mixed one was found in case of the 17Mn1Si steel. The reasons for the material embrittlement may include various mechanisms but most obvious in this case are the mechanisms of hydrogen embrittlement with the formation of microlaminations during operation of the gas pipeline [13]. As a result, the crack propagates in the body of the grain and along the grain boundary. A decrease in the step of striations, which was observed in this zone, is preconditioned by relaxation processes at the crack tip, caused by interactions with dispersed defects, and the involvement of additional sliding systems, etc. [14, 15]. Apart from fatigue striations, there are local sections of spalling on the fatigue fracture surface, which are surrounded by narrow areas of ductile fracture. The fatigue crack front crossed laminations of microcracks several times, which appeared in the metal due to in-service hydrogenation. It is within these sections that we found a decrease in the step of fatigue striations, which is caused by a local change in the stress-strain state at the fatigue crack tip [16].

Offshore pipelines. We have established that the increased amplitude of cyclic loading reduces the cyclic durability of the pipe material (Figure 4 a).

For σ_a = 260 MPa, cyclic durability does not depend on the preliminary deformation. Materials in the initial state and after preliminary plastic deformation (PPD) have the same operation cycle count ($N_f \sim 51,000$ cycles).

For σ_a = 320 MPa, cyclic durability of preliminarily deformed 09Mn2Si steel decreases. Particularly, for S-lay method the durability decreased by 26%, while for the J-lay method this value is 13% as compared to undeformed material ($N_f = 23,000$ cycles).

For σ_a = 420 MPa, cyclic durability of preliminarily deformed 09Mn2Si steel increases. For S-lay method the increase amounted to 29%, while for J-lay method the value grew by 57% as compared to undeformed material ($N_f = 2,800$ cycles). In absolute terms, the operation cycle count of the specimen is growing but this effect is specific only for large loading amplitudes. In addition, taking into account that such loading amplitudes are specific for materials with inconsiderable durability, the practical significance of such phenomenon is more likely of scientific rather than of practical interest. The opposite character of the change in cyclic operation time for medium and high amplitudes manifests the difference in the kinetics of accumulated dispersed structural and mechanical defects in 09Mn2Si steel after the deformation at different amplitudes of cyclic deformation. Some aspects of these degradation processes are reflected in specimen fracture and can be detected by fractography [16].

4 Macroanalysis of specimen fractures

Analysis of specimen fractures included the comparison of the surface morphology formed at different stages of fatigue crack growth. In all investigated specimens we have detected several common areas (Figure 5).

1. “Smooth” subsurface layer is typical for a fatigue failure. The cyclic loading there caused the accumulation of structural and mechanical defects in the ma-

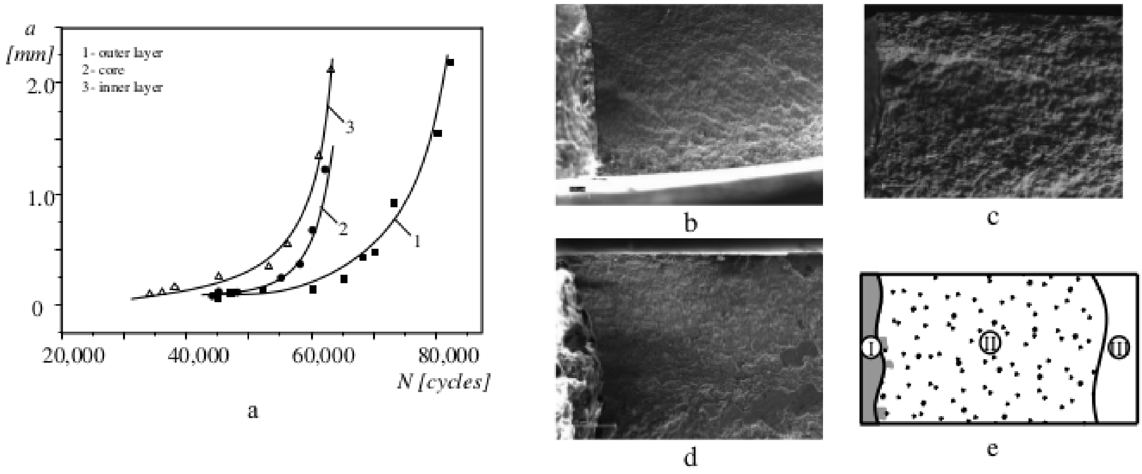

Figure 2: Regularities of crack growth. a) dependence of crack length on the number of loading cycles, b) micromechanisms of failure of 17Mn1Si steel in the outer layer of a pipe, c) in its core, d) in the inner layer; e) is the layout of layers.

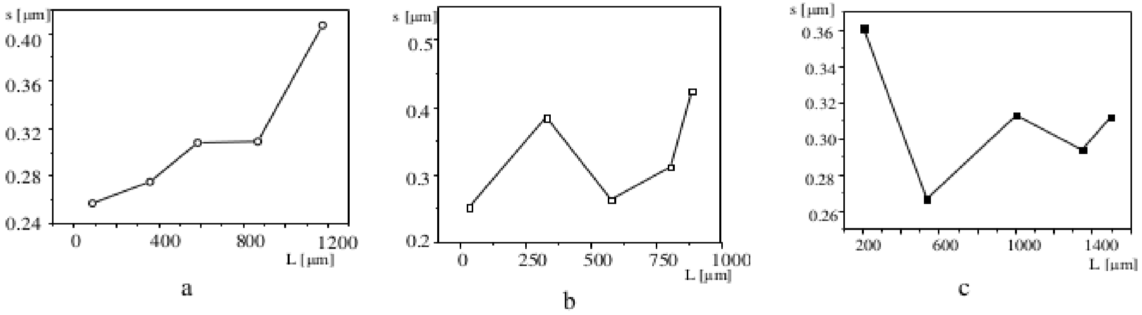

Figure 3: Dependence of the step of fatigue striations on fatigue crack length. a) the outer section of a pipe, b) the core of a pipe and c) inner section of the pipe.

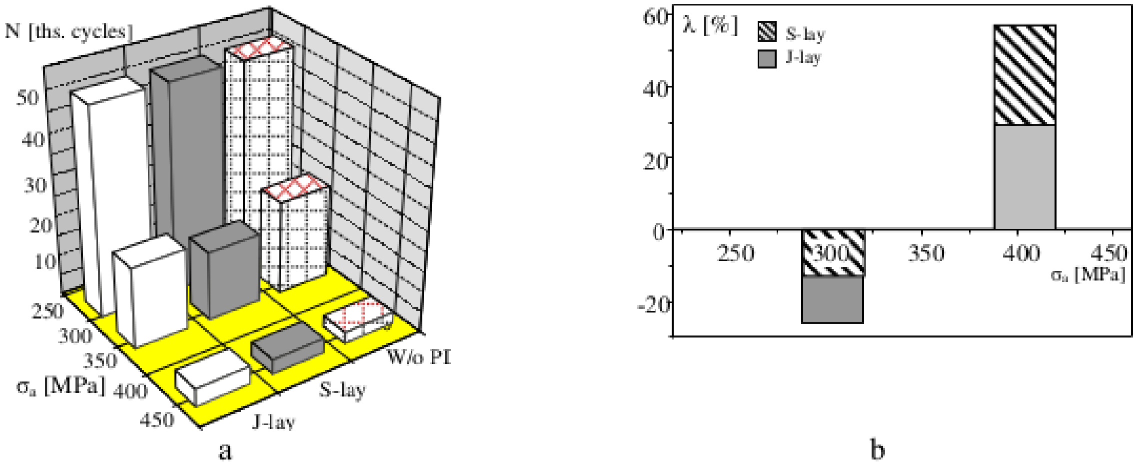

Figure 4: Cyclic durability of specimens after different schemes of preliminary deformation (PD) and relative values of operation cycles ($\lambda = (N_0 - N_{PD})/N_0$).

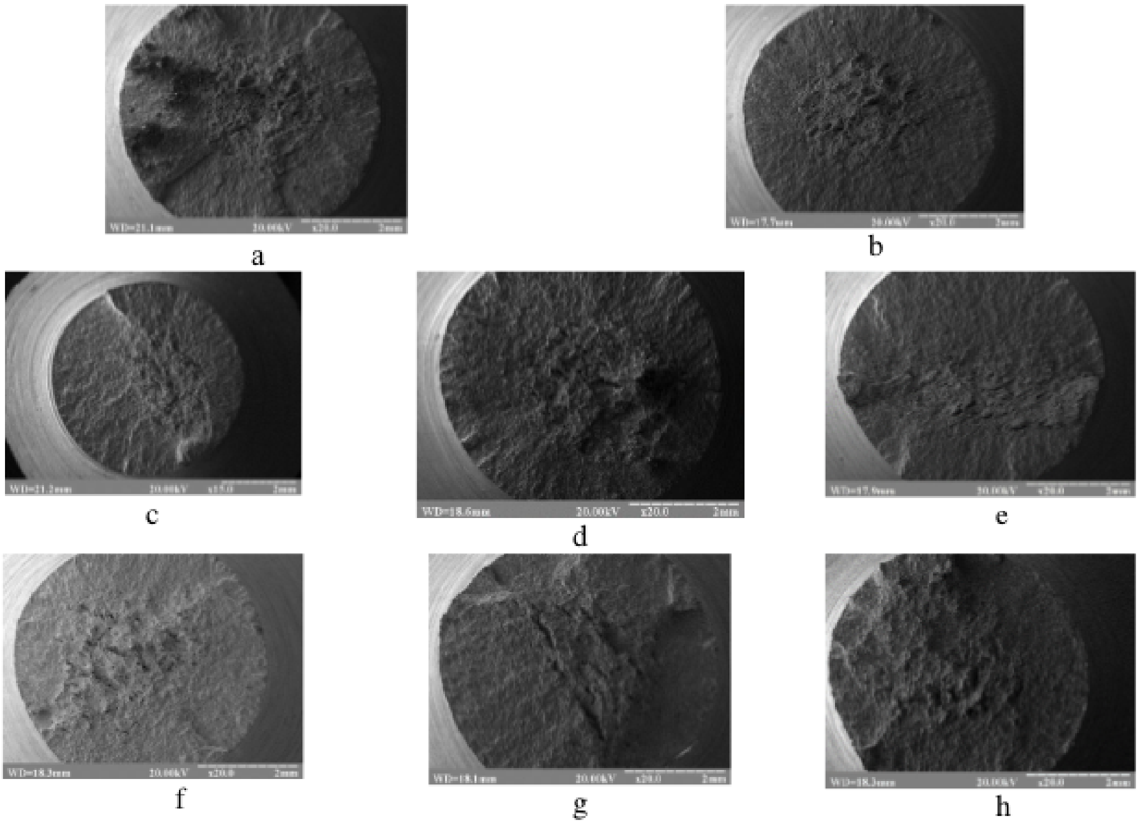

Figure 5: Mechanisms of cyclic failure of 09Mn2Si steel. At $\sigma_a = 260$ MPa, a) without PD and b) with PD by S-lay method; at $\sigma_a = 320$ MPa, c) without PD, d) with PD by S-lay method and e) with PD by J-lay method; at $\sigma_a = 420$ MPa, f) without PD, g) with PD by S-lay method and h) with PD by J-lay method.

Table 4: Mechanisms of the fatigue fracture of specimens from Steel 09Mn2Si.

σ_a, MPa	Mechanisms of cyclic deformation and failure	
	Crack nucleation	Pre-critical crack growth
260	The analysis of the fracture area indicates the non-uniformity of deformation in the specimen cross-section, which impedes crystallographic shears. Fatigue fracture took place by the scheme "shear + turn".	Plastic macrodeformations of the specimen by the scheme of pure bending. Fracture by the mechanism of plastic separation.
320	The intensive deformation of the material took place with the activation of shear mechanisms of the fatigue crack propagation, and the formation of facets covered with fatigue striations.	Traces of macrodeformation of specimens under a combined effect of shear and separation are noticeable on the surface of the fracture area.
420	Significant plastic deformation of the material with the formation of macrobands of plastic deformation, and large facets with ductile failure between them.	A significant effect of strain localization at the mesolevel provides a gradual transition of deformation and fracture processes from the microlevel to the macrolevel with a significant plasticity in the fracture area, as evidenced by separation pits.

terial (at microlevel). The processes of fatigue failure always begin from a surface, while the environment plays an important role. Then, the microdefects were formed and propagated further (mesolevel). The outlined morphological features of the crack formation zone and discovered decrease in the number of material crack formation centers induced by raised loading amplitude evidence the accumulation of multiple microdamages [18]. Such effect is accompanied by the generation of microdefect formation regions, the conditions of external cyclic loading being constant. Microcracks propagating in all directions aggregate causing the deformation of adjacent areas and forming lamellar tears on the surface of a fatigue damage zone. The size (height) of such tears increases with an increasing loading amplitude. However, we should point out that in general the surface is visually perceived as fairly smooth. Investigation of the surface of specimens with high magnification revealed its lamellar relief and individual striations. Periodic cyclic loading of the material and accumulated damages facilitate shear deformations in the material, while the growth of loading amplitude lead to increased size of irregularities [19].

2. The inner surface was formed as a result of the quasistatic fracture of specimens. Such surface structure is stipulated by rotational instability of the material at the top of a crack and by accommodation accumulation of damages under cyclic bending of a specimen.

5 Discussion of regularities of plastic deformation affecting the life of a pipe

We have revealed two main effects of the loading amplitude:

Reduction of life at average loading amplitudes. Plastic deformation of 09Mn2Si steel causes decreased plasticity of a specimen, while cyclic stress is insufficient for the generation of local plastic deformations that would result in at least partial relaxation processes in the material. The cycling induces the intense accumulation of damages in the surface (deformed) of the specimens, which is evident in fractographs. The accumulation of dispersed defects is accompanied by the formation and aggregation of microcracks, which lowers the cyclic durability of a material [20–22].

Increase in life at high loading amplitudes. The study of causes increasing the strength of 09Mn2Si steel has established that the preliminary deformation of specimens induces the redistribution of stress and the accumulation of structural defects as well. On the one hand, microplastic deformations in the material condition its hardening but under cyclic deformation they serve as locations of accumulated local damages that lead to lamination and cracking.

The process of microstrain accumulation and microdefect nucleation caused by pipe laying works affects their cyclic life. Therefore, it is necessary to systematize the mechanisms of their deformation and fracture under various amplitudes of cyclic loading. Crack start and propagation mechanisms for the investigated specimens are generalized in Table 4.

6 Conclusion

The work has discovered and quantitatively characterized the main regularities of a fatigue crack growth process in specimens made of 17Mn1Si steel. The study has also established that the maximum cyclic durability is specific for the outer layer of a pipeline. This is an assumption of a more careful control of pipe defects (primarily pittings) penetrating to a considerable depth of a pipe wall. The presence of such defects is potentially dangerous because the crack resistance of inner layers is about 1.3 times lower than that of outer ones.

We have defined physical and mechanical regularities of the cyclic durability of a marine pipeline material after pipe installation. We have established that the installation of a pipe does not affect the cyclic durability for the loading amplitude $\sigma_a = 260$ MPa. The increased loading amplitude to $\sigma_a = 320$ MPa causes a reduction in the cyclic durability of a deformed 09Mn2Si steel specimen subjected to simulated S-lay installation by 26%, for the J-lay method the decrease is 13%. For higher loading amplitude of $\sigma_a = 420$ MPa, the cyclic durability of preliminarily deformed 09Mn2Si steel increases. Particularly, for S-lay installation method the growth amounted to 29%, for J-lay method the increase amounted to 57%.

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