STRUCTURE AND FATIGUE DURABILITY OF 09Mn2Si PIPE STEEL AFTER LONG-TERM OPERATION IN FAR NORTH CONDITIONS

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A comprehensive study of the structure and fatigue durability of the 09Mn2Si steel used for constructing the Mastakh-Berge-Yakutsk main gas pipeline (taken from the linear part with an outer diameter of 530 mm and a wall thickness of 7mm) after 37 years of operation is carried out. A comparative analysis of the results obtained for the emergency stock steel is made. It is shown that long-term operation does not give rise to a substantial redistribution of cementite. Deformation aging is slightly expressed, and it is manifested through the precipitation of finely dispersed carbides in the grain bulk. The revealed structure degradation practically does not make sense under static tension or hardness measurement. At the same time, under cyclic testing, the microstructure degradation occurring during long-term operation results in a fatigue lifetime decrease, especially at the stage of crack initiation.

Keywords: pipe steel, fatigue durability, structure degradation.

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1. Introduction

Main oil and gas pipelines are strategic industrial facilities; therefore, monitoring their mechanical state and investigating the reasons for their structure degradation during long-term operation are actual scientific and engineering problems [1]. This paper studies the degradation of the 09Mn2Si steel of the Mastakh-Berge-Yakutsk main gas pipeline after 37 years of operation. Pipes in the pipeline are permanently repaired and replaced due to failures, which were accompanied by a number of catastrophic incidents [2]. The main factors causing the failure of pipeline components are complex climatic conditions, corrosive wear [3] during operation, and also deformation aging [4] induced by prolonged exposure to static loads, heterogeneity in the structure of the steel. In this concern, the study of metal structure degradation processes and their effect on the mechanical properties of the 09Mn2Si pipe steel are of importance for understanding and developing techniques for the retardation of structural changes during long-term operation. For this reason, the aim of the study is to estimate the effect of the long-term operation of the 09Mn2Si steel (for 37 years) under the Far North conditions on the microstructure degradation, as well as to investigate the mechanisms of its failure under static and cyclic loadings.

2. Experimental

The 09Mn2Si steel under study had a structure of hot-rolled sheets. Specimens were cut out from fragments of two pipes, 530 mm in diameter: after a long-term operation (from 1972 to 2009), as well as from the emergency stock that had been stored in the field within the same time. To compare and evaluate the degradation processes that occurred in the fragment after a long-term operation, the structure and mechanical properties of the steel from the emergency reserve (considered as non-deformed or standard) were studied.

Static tension tests were conducted with the use of an Instron 5582 electromechanical testing machine; the loading rate made 0.3 mm/min. The specimens for static and cyclic tension tests were dog-bone-shaped, with dimensions of 50×7×1 mm and a gauge length of 20×5×1 mm. Cyclic tension tests were performed with the use of a Biss UTM 150 servo-hydraulic testing machine. The cycle asymmetry was $R = 0.1$; the maximum load in the cycle was equal to 280 MPa, the loading frequency was 20 Hz. To localize the processes of fatigue crack nucleation, an I-shaped stress riser (notch) with a length of ~ 400 μm and a tip radius of 125 μm was applied to the specimens. The interval for image capturing made 1,000 cycles. The recorded images were processed and analyzed with the help of Vic-3D 7 software with preliminary estimation of calculation parameters by the automatic algorithm. The microhardness was measured with the help of a PMT-3 device with a load onto the Vickers pyramid of 0.98 N (100 g). The fine structure was analyzed with the use of a Philips SM-12 transmission electron microscope.

3. Results

The steel from the emergency stock has a ferrite-pearlite structure (fig. 1, *a*). The perlite content makes ~16 ± 1%; a pronounced striped texture is observed. The average grain size is equal to 9.5 ± 1 μm. The steel after 37 years of operation also has a ferrite-pearlite structure. The perlite content makes ~ 12 ± 0.6 %; the pearlitic colonies are small, and they are located mainly along the grain boundaries (fig. 1, *d*). The average grain size of this fragment is equal to 11 ± 1 μm. Thus, during operation, the content of the pearlite phase in the 09Mn2Si steel has decreased by ~ 5 %. It is may have come from hydrogenation, as a result of prolonged exposure to a gaseous medium. The decrease in the carbon content is also accompanied by a slight increase in the size of ferritic grains (by ~ 10 %).

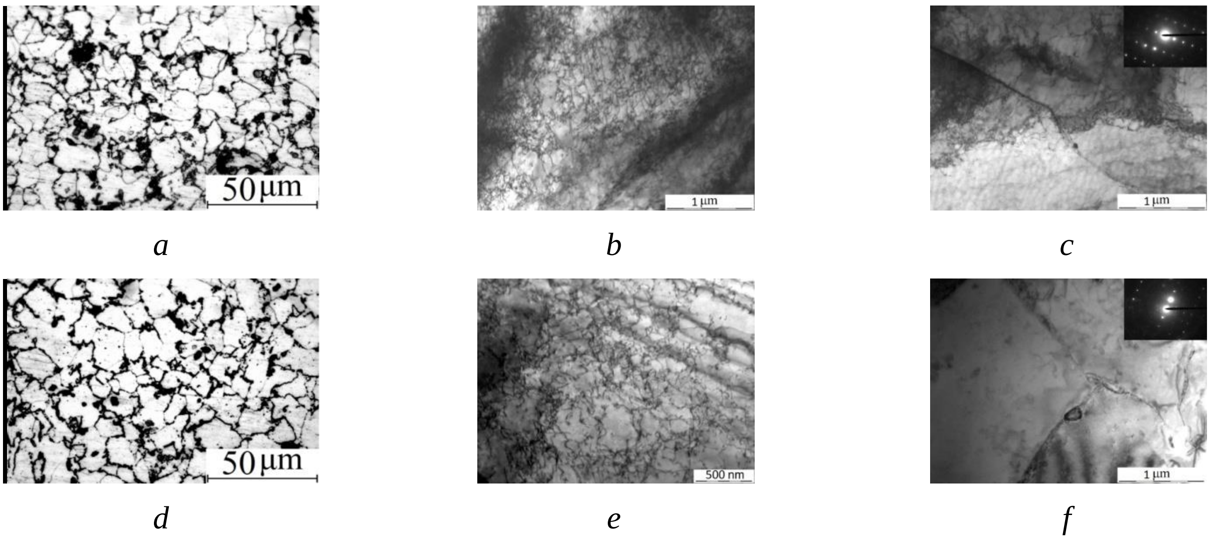


Fig. 1. The microstructure (*a, d*) and TEM-micrographs (*b, c, e, f*) of steel fragments from the emergency reserve (*a, b, c*) and after long-term operation (*d, e, f*)

In the material bulk of both steel fragments, a ferrite structure with cementite plates along the grain boundaries is observed by transmission electron microscopy. Large uniaxial cementite particles (100–500 nm) are located both in the grain bodies and along the grain boundaries (fig. 1, *c*, *f*). The dislocation density for the stock steel is higher, 10^{10} to 10^{11} cm^{-2}, while after the operation it is 10^9 to 10^{10} cm^{-2} (fig. 1, *b*, *e*). It is known from the literature [1] that long-term operation of steel may give rise both to already mentioned hydrogenation and to structural degradation processes expressed through deformation and crushing of cementite along the boundaries of ferrite grains, the formation of carbide precipitates there, as well as through the evolution of the dislocation substructure due to deformation aging.

At the initial stages the deformation aging is expressed through the formation of Cottrell atmospheres and dislocation pinning. The latter results from the precipitation of highly dispersed carbides in the grain bodies. Pipes for the main gas pipeline construction are manufactured with a large safety margin for safe operation during dozens of years. This is why, after 37 years of operation, the steel is unlikely to experience significant stresses, which may give rise to severe plastic deformation or deformation aging. The operating temperature range also fluctuates within acceptable limits, which should not result in noticeable structure modification. This is confirmed by the TEM data; namely, the carbides of the steels in both states are located in the grain bodies and along the grain boundaries. Cementite plates at the grain boundaries are not fractured. Thus, it can be assumed that deformation aging could occur only at the initial operation stage (the formation of Cottrell atmospheres and dislocation pinning), which is confirmed by an approximately one order difference in the dislocation density between the reserve stock fragment and the one after operation. These changes have no significant effect on hardness, but they may affect the decrease of toughness or the shift of the cold embrittlement threshold towards higher temperatures.

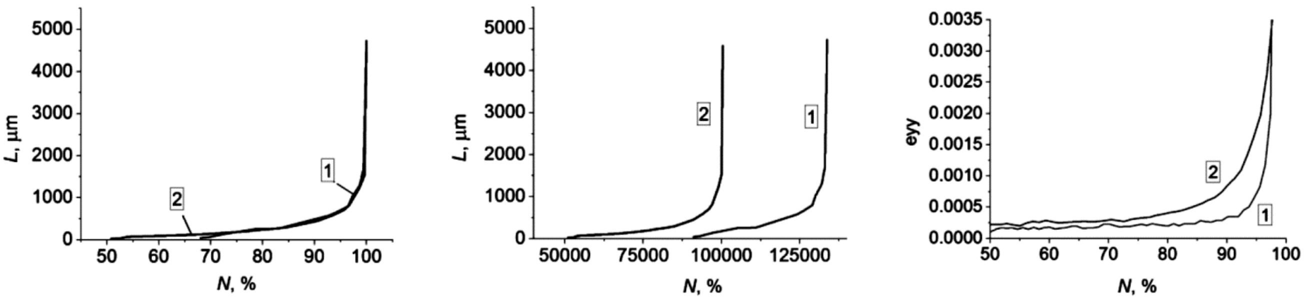
The microhardness results obtained for the steel after the long-term operation (tab. 1) can be interpreted in terms of the development of two competing processes, which are i) hardness reduction as a result of decarburization and ii) strain hardening due to dislocation pinning. Mutual compensation of these processes can maintain the hardness of the steel after operation at the initial level, while giving rise to a different deformation behavior as compared to the reserve stock steel fragment.

A yield tooth and a yield plateau are observed on the loading diagrams of the 09Mn2Si steel specimens in both states. Their presence is attributed to the low-carbon "status" of this steel. In addition, this agrees well with the results of the fine microstructure observation indicating low dislocation density at the beginning of plastic flow. The specimens of the reserve stock steel, as well as the one after the operation, possess a similar value of tensile strength. At the same time, the specimens from the emergency reserve have a lower yield stress (↓ by 27 %), but, simultaneously, higher ductility (↑ by 31 %) (tab. 1). This difference is most likely to arise from a larger pearlite phase volume and a slightly smaller grain size.

The fatigue lifetime of the 09Mn2Si steel after long-time operation decreases by 16 %, from $N = 1.25\times10^5 \pm 0.16\times10^5$ (emergency reserve) to $N = 1.05*10^5 \pm 0.18\times10^5$ cycles (after operation). Graphs illustrating the dependence of crack length versus the number of loading cycles are plotted in fig. 2.

Table 1 – Mechanical properties of the 09Mn2Si steel measured under static tension

Material type	Conventional yield strength ($\sigma_{0.2}$), MPa	Tensile strength, (σ_U), MPa	Elongation, δ, %	Contraction, φ, %	H_μ, GPa
Reserve stock steel	310 ± 20	490 ± 25	34 ± 2	6.6 ± 1	1.94 ± 0.05
After the operation	380 ± 20	500 ± 20	31 ± 3	6.6 ± 1	2.05 ± 0.04



a *b* *c*

Fig. 2. Diagrams of fatigue crack growth versus *a*) the normalized number of cycles, *b*) the absolute number of cycles; *c*) dependences of longitudinal strain on cyclic loading (in percent prior to failure); 1 – emergency stock; 2 – after long-term use

It follows from the analysis of the data given in normalized coordinates (fig. 2, *a*) that crack propagation looks similar (although in the reserve stock material the crack nucleates later (for comparison $N_{\mathrm{I\ oper}}$ ~ 50 % and $N_{\mathrm{I\ res}}$ ~ 68 %). The analysis of the crack growth diagrams plotted in the absolute coordinates (fig. 2, *b*) also shows that crack initiation in the emergency stock specimen occurs later. In general, in the specimens after operation the main fatigue crack originates earlier, while the plastic deformation accompanying the crack propagation is localized to a greater extent. This is confirmed by the graphs depicting the dependence of the longitudinal strain component versus the number of cycles prior to failure (the normalized value expressed in percent, fig. 2, *c*).

Thus, despite the shape similarity of the crack growth diagrams for the specimens of both types (when they are plotted in normalized coordinates (fig. 2, *a*, *b*)), it is the difference in the graphs of the transverse strain component that is the reason for the decrease in the fatigue life of the specimen after the long-term use. Namely, the exhaustion of plasticity does not allow the propagation of the main fatigue crack to be effectively resisted.

4. Conclusion

It has been shown that long-term operation does not result in a noticeable redistribution of cementite, since, while being in use, pipes operate under low pressures and at low temperatures. However, hydrogenation may occur, which may give rise to decarburization. Deformation aging is poorly expressed, and it is manifested through the precipitation of finely dispersed carbides in the grain bodies.

The revealed structure degradation has little effect on the mechanical properties determined in static tension tests and hardness measurements. This is attributable to the development of two competing; namely, i) softening as a result of decarburization and ii) hardening as a result of dislocation pinning onto carbide precipitates.

The fatigue durability of the steel after long-term operation has decreased by ~ 16%. It has been demonstrated that in the degraded steel the main fatigue crack originates earlier due to the accumulation of structural and mechanical defects in the material. The calculated dependences of the transverse strain component versus specimen displacement indicate microstructural changes, which result in lower ductility, the latter being caused by sensitivity to the accumulation of fatigue damages, especially at the stage of fatigue crack initiation.

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