

2nd International Conference on Structural Integrity, ICSI 2017, 4-7 September 2017, Funchal, Madeira, Portugal

Influence of long-term operation on structure, fatigue durability and impact toughness of 09Mn2Si pipe steel

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Abstract. A comprehensive study of the structure, mechanical properties including impact toughness of 09Mn2Si steel used for constructing main gas pipeline "Mastakh-Berge-Yakutsk" after 37 years of operation was carried out. A comparative analysis of the results obtained for the emergency stock steel was conducted. It is shown that long-term operation does not give rise to a substantial redistribution of cementite. Deformation aging is slightly expressed and is manifested through the precipitation of finely dispersed carbides in the grain bulk. The revealed structure degradation does not practically make sense under static tension or hardness measurement. At the same time, under cyclic testing the microstructure degradation being occurred during long-term operation results in fatigue lifetime decrease especially at the stage of crack initiation. The most pronounced manifestation of structure changes is related to decreasing impact toughness of 09Mn2Si steel which reaches ~ 2 times under negative temperatures. The reasons and mechanisms of the observed phenomena are discussed.

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Peer-review under responsibility of the Scientific Committee of ICSI 2017

Keywords: pipe steel 09Mn2Si; long-term operation; microstructure degradation; embrittlement; impact toughness; fatigue durability.

1. Introduction

Main oil and gas pipelines are strategic industrial facilities and monitoring their mechanical state as well as

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investigating the reasons of their structure degradation during long term operation are actual scientific and engineering problems. A large number of research papers on study the impact of various factors (internal gas pressure, stresses, the presence of moisture, hydrodynamic and temperature effects) on the intensity of degradation processes of main gas pipelines have been published [1-3]. These studies are of special importance for oil and gas pipelines that operate for a long time in the Far North where annual temperature variation can reach 100 °C [4].

Degradation of 09Mn2Si steel of the main gas pipeline "Mastah-Berge-Yakutsk" was investigated in this paper. Repair and replacement of pipes permanently take place at the pipeline being related to their failures which were accompanied by a number of catastrophic incidents [5]. The main factors to give rise to the failure of pipeline components are complex climatic conditions, corrosive wear [6] during operation, and also deformation aging [7] induced by prolonged exposure to static loads, heterogeneity in the structure of the steel, and earth ground motion. A generalization of the results of our earlier studies suggests that the continued operation of the gas pipeline might give rise to the accumulation of diffuse structural-mechanical defects in the steel [8]. At the same time, a reliable assessment of its technical state demands for a comprehensive analysis of the steel structure degradation [9].

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 retardation structural changes during long-term operation. It is known that for low-carbon pipe steel of ferrite-pearlite grade with a BCC-structure that operates under low temperatures the cold embrittlement threshold (indicating sharp decrease of the impact toughness) is a key limitation factor [10].

The rest of the standard mechanical characteristics (yield point and ultimate strength, the value of elongation at break, etc.) may not vary noticeably with the decrease of the testing temperature. For this reason, it is also of great practical interest to estimate the changing the impact toughness of 09Mn2Si steel after a long-term operation in a wide range of testing temperatures including those below the cold embrittlement threshold.

The aim of the study is to estimate the effect of the long-term operation of 09Mn2Si steel (during 37 years) under the Far North conditions on the microstructure degradation as well as to investigate the mechanisms of its failure under static, cyclic and dynamic loadings.

2. Experimental

The 09Mn2Si steel under study had the structure of hot-rolled sheets. Specimens were cut out from fragments of two pipes: after the long-term operation (from 1972 till 2009) as well as from the emergency stock that was stored in the field during the same time. A study of the long-term loading effect on the structure and mechanical properties of 09Mn2Si steel was carried out with the use of pipe fragments with the diameter 530 mm of the main gas pipeline "Mastakh-Berge-Yakutsk". To compare and evaluate the degradation processes that occurred in the fragment after a long-term operation the structure and mechanical properties of steel from the emergency reserve (being considered as non-deformed or standard) were studied.

Specimens were cut from pipe fragments along the transverse direction by the electric spark machine. Specimens for static and cyclic tension tests were dog-born shaped with the dimensions of 50×7×1 mm and a gauge length of 20×5×1 mm. Static tension tests were conducted with the use of electromechanical testing machine Instron 5582; the loading rate made 0.3 mm/min. Specimen surface characterization was conducted with the use of interferometer NewView 6200 (Zygo). The cyclic tension tests were performed with the use of Biss UTM 150 servo-hydraulic testing machine. The cycle asymmetry made $R = 0.1$; 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 the 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 impact toughness was determined with the use of Charpy specimens measuring 55×7×7 mm with a V-shaped notch of 2 mm deep. For this, the Instron 450MPX automated impact pendulum was employed with measurement procedure taken according to ASTM E 23: 2007. The tests were carried out at the following temperatures: +20, 0, -20, -40 and -70 °C. The specimens were cooled with help of fridge chamber Lauda RP 870 during 10 minutes just before the testing.

The properties degradation was analyzed being based on a comparison of 09Mn2Si steel specimens taken in the two various states. For this, the normalized value of the factor $\lambda_\varphi = (\varphi_0 - \varphi_c)/\varphi_0$ (where φ_0 is the value of the parameter for the non-deformed material, while φ_c – the value of the material parameter after the long-term operation) was used.

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