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Effect of long-term operation on steels of main gas pipeline. Reduction of static fracture toughness

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ABSTRACT

The effect of the long-term operation on changes in the parameters of fracture toughness and a tendency for a delayed fracture of the steel of main gas pipelines is investigated. Based on the method of the full strain diagrams the general regularities of operational degradation influence onto the static fracture toughness and microscale failure mechanisms of 17MnSi steel after long term operation have been established. Generalization of results on the influence of absorbed hydrogen onto the pipeline steel structure and fracture pattern made possible to systemize the data on dispersed damage accumulation. The schematization of fracture mechanisms of 17MnSi steel is offered. The proposed approaches to the study of static fracture toughness of the steel of the main gas pipelines can be used in the evaluation of their technical conditions and planning of their overhaul.

1. Introduction

It is well known that long-term operation gives rise to the degradation of physical and mechanical properties of the metal of main gas pipelines (Filippov et al., 2013). This is primarily related to the changing in the structural state that comes from the impact of technological stresses, subsidence of soils, exposure to corrosive environments, hydrogen embrittlement, etc. Influence of the operational factors results in the decrease of the mechanical properties of pipeline materials and increases the probability of their fracture under loading values that do not exceed the maximum allowable designed ones (Filippov et al., 2013; Nykyforchyn et al., 2009a,b).

In this paper, the effect of the long-term operation on the structure and mechanical properties of the metal of pipes with longitudinal welds performed by electric arc welding of gas mains is investigated. Steel 17MnSi had been used for the manufacturing of such pipes for about 40 years, and later they began to use steel 17Mn1Si. Pipes made of steel 17Mn1Si (or earlier modification 17MnSi) were used in the construction of a significant part of the main gas pipelines in Ukraine (Maruschak et al., 2016a,b). The analysis of literature data (Nykyforchyn et al., 2009a,b; Capelle et al., 2008; Andreikiv et al., 2012) makes possible to systemize the processes of aging and hydrogen absorption in materials of gas and oil pipelines. At the same time, in order to prevent premature brittle fracture of main gas pipelines and provide reliable evaluation of their residual life time one should rely on the actual structure and properties of the steel under inspection.

The approach to evaluate the mechanical state of the material through taking into account the level of structural defects is known as the method of “full strain diagrams”. The latter, i.e. “stress - strain” curve that include the second dropping section (down to the horizontal axis) makes possible to determine the parameters of strength, ductility and crack resistance of materials (Lebedev and Chausov, 2004). This method is very sensitive to structural changes, accumulation of local micro-defects and micro-cracks which reduce the resistance of the metal to failure. A subsequent fractographic analysis of the specimens under investigation allows gaining detailed information on the mechanisms of deformation and fracture of the material.

The aim of this paper is to study the mechanisms of degradation of main gas pipeline steels and their influence on the static fracture toughness and mechanisms of failure of the 17MnSi steel.

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1.1. Determination of the static fracture toughness

Templates were taken from the sections of gas mains operating in the same power and climatic conditions and in the same region of Ukraine (Poltava region). The production technology for the rolled steel used in the manufacture of pipes was the same and corresponded to GOST 19282-73. Therefore, we investigated and compared the condition of their metal. To determine the mechanical properties of steel 17MnSi, specimens with diameter of 5 mm and a gauge length of 25 mm were used, which were cut from the pipe in the longitudinal directions.

Experiments were conducted on the upgraded testing machine ZD-100Pu, which is equipped with two special devices: to record the complete diagrams and to provide impulse uploads at any given level of the initial static strain, Fig. 1. A new type of mechanical testing developed by (Lebedev et al., 1986; Lebedev and Chausov, 1992; Chausov et al., 2004) has been applied in this study and described in various papers. Specimens of pipe steel were statically stretched, then complete stress-strain diagrams were recorded.

By taking into account the structural and non-uniform striped (texturized) microstructure pattern of the 17MnSi steel it might be assumed that accumulation of damages in the material will also possess the “ordered” character (Maruschak et al., 2016a,b). By employing the full strain diagrams technique one can accurately determine the fracture toughness in the material after the main macro-crack formation in the neck. Evaluation of the ultimate damage of the 17MnSi steel was carried out using the specific work of fracture (Lebedev and Chausov, 2004):

$$A_p = \varepsilon_f \cdot S_k,$$

It is known that operation ensures the reduction of the static fracture toughness of materials. The latter is most significantly declined after the long-term operation (over 30 years).

To evaluate the fracture toughness of materials let us use the following parameter K_λ (Lebedev and Chausov, 2004):

$$K_\lambda = \sqrt{S_k \cdot \Delta l_p \cdot E},$$

where S_k – tearing-off resistance of the material; $\overline{\Delta l_p}$ – the value of elongation at the stage of cleavage microcrack growth; E – Young's modulus.

The K_λ criterion is an analog of the force one at fracture toughness test K_{IC} and is related to the following dependence (Lebedev and Chausov, 2004):

$$K_{IC} = \alpha \cdot K_\lambda,$$

where α – the proportionality factor (for steels it is equal to 0.23) (Lebedev and Chausov, 2004).

1.2. Research results and their discussion

The operation of the material gives rise to the accumulation of structural damages, increasing of the of micro-defects concentration in the local regions, embrittlement and reduction in static fracture toughness. Initially, the 17MnSi steel has the value of $K_{Ic} = 108$ MPa × m^{-2}, while for gas pipelines after exploitation the static fracture toughness values is decreased down to $K_{Ic} = 97$ MPa × m^{-2} and $K_{Ic} = 71$ MPa × m^{-2}, respectively. The values of K_λ и K_{IC} for 17MnSi steels are shown in Table 2.

Currently, there is a slight increase in the number of accidents in

Table 1
Steel 17MnSi in the initial state and after long term operation.

No.	Main gas pipeline	Operating time, years
1.	Steel reserve (Initial state)	no
2.	«Shebelinka-Dykanka Kiev»	38
3.	«Elets-Dykanka Kiev»	31

Table 2
Parameters of the static fracture toughness of 17MnSi steel in initial state and after the long-term operation.

Main gas pipeline	Resistance to tearing-off and static fracture toughness			
	S_k, GPa	K_λ, MPa × м$^{-2}$	A_p, kg/mm^3	K_{Ic}, MPa × m^{-2}
Steel from the reserve (the initial state)	1.08	471	6.0	108
“Shebelinka – Dykanka – Kiev”	1.04	422	4.7	97
“Elets – Dykanka – Kiev”	0.579	309	2.7	71

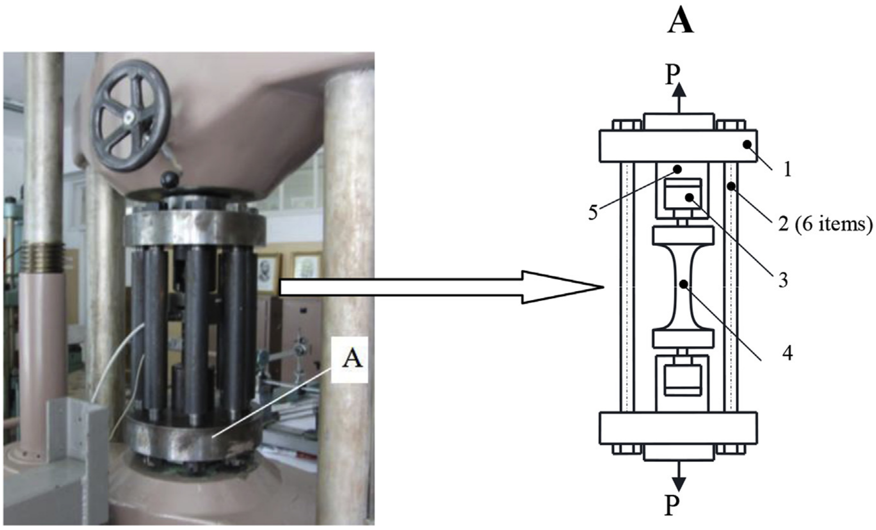

Fig. 1. General view of the test setup with an installed specimen (load frame of the setup – outer contour); A - inner contour: 1 - flanges; 2 – strain-gauge rods; 3 - spherical supports; 4 - spherical supports; 5 - dynamometer.