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SHORT COMMUNICATION

Effect of long-term operation on steels of main gas pipeline: Structural and mechanical degradation

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Abstract Based on the results of experimental studies of 17MnSi steel the regularities of the in-service degradation influence into its deformation and strength properties were established with the use of full strain diagrams. The important role of the hydrogen absorption that takes place under operation and its negative influence onto the mechanical properties of 17MnSi steel are shown. The latter is manifested through the microdefect growth in the gas pipeline material wall (in the form of dispersed damages) and reduction of its resistance to the brittle fracture.

1. Introduction

Ensuring operational reliability of the main gas pipelines calls for running routine diagnostic procedures and evaluation of the technical state of the base metal and welds by non-destructive testing methods (Aleksandrov et al., 2011). Currently, the most advanced approach in the defectoscopy of such objects is use of intratubal inspection systems. They make possible quick identification of defects and pipe-line regions that require repair or replacement (Arafin and Szpunar, 2009). However, a long time operation of the main gas pipelines gives rise to metal degradation even in "unimpacted" sections of the pipe.

It is known that under the influence of a number of energy factors (technological pressure, temperature of the transported product, bending moments, etc.) as well as the physical and chemical processes to take place in steel pipelines the irreversible structural changes that can be regarded as a manifestation of "dispersed damage" happen (Mohtadi-Bonab et al., 2015; Lebedev and Chausov, 2004). These microstructural defects reduce the bearing capacity and fracture toughness of metal pipelines. However, the most of these sections still possess adequate safety factor and can be used for a long time, providing clarification of the current state and mechanical

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properties of the metal takes place regularly (Mohtadi-Bonab et al., 2015).

There are some studies available that are devoted to these issues where double–criteria approaches to the integrity assessment of a pipe having technological and operational defects are developed (Lebedev and Chausov, 2004; Kotrechko et al., 2004). Mechanisms of degradation and fracture caused by the corrosive factors are also actively studied. As a rule, such kinds of aging of the metal and local corrosion of the surfaces of the pipes are associated with the combined effect of the soil environment and operating loads (Nykyforchyn et al., 2009). The corrosion of the inner surface is typical, most often, of the industrial gas pipelines used for the transportation of highly aggressive media (Hembara and Andreikiv, 2012). However, even small amounts of moisture, salts, organic substances, CO_2, and sulfur-containing substances present in the purified gas can also initiate and accelerate this type of corrosion (Nykyforchyn, 2013; Gabetta et al., 2008). Since we speak about degradation not only on the surface of the metal operating in contact with aggressive media but also in the bulk of the material, this influence can be explained only by the action of hydrogen released as a result of the corrosion processes and penetrating in steel down to depths comparable with the thickness of the pipe walls (Capelle et al., 2010; Tsyrul'nyk et al., 2007). A similar approach to the evaluation of hydrogen degradation of steels after long periods of operation can also be used in the case of gas mains pipe. However, in this case, it is necessary to solve the problem of sensitivity of various parameters that can be used for the evaluation of the serviceability of gas mains pipe or the residual service life prior to the degradation of the metal.

All this allows us to use two basic approaches to the assessment of the technical state of materials and structures: i) based on the planned designed life-time and ii) taking into account the actual state (Maruschak et al., 2014). Operation within the prescribed resource is based on the principle of guaranteed safe operating period. The inspection through revealing the actual mechanical state allows analyzing objects and predicting their residual life-time by taking into account operational damages and degradation processes in the material (Krasovskii and Orynyak (2010)).

This paper is aimed at establishing the general laws of damage accumulation in the 17MnSi steel and assessing their impact onto the strength of main gas pipelines metal after prolonged use.

2. Methods

17MnSi steel of the main gas pipelines with a diameter of 1020 mm and a wall thickness of 10 mm after various operation terms was investigated (Table 1). Cylindrical shape specimens were cut parallel to the longitudinal axis of the pipe with a diameter at gauge length of 5.0 mm. Experiments were carried out with the use of modernized hydraulic testing machine primarily designed for static testing ZD-100Pu with a registration of full strain diagram of the material under loading.

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

No.	Main gas pipeline	Operating time, years
1.	Steel from the reserve (initial state)	–
2.	«Shebelinka – Dykanka – Kiev»	38
3.	«Elets – Dykanka – Kiev»	31

During the tests, transverse and longitudinal contractions of the specimen were registered with the use of an extensometer. Flat test coupons with gauge length of 10×50 mm and thickness of 5 mm were employed. Digital images of specimen surfaces were taken with the use of the DSLR camera "Canon D550" installed onto the optical microscope MBS-10.

Relative strain was calculated by the following formula (Lebedev and Chausov, 2004):

$$\varepsilon = \varepsilon_l + \varepsilon_p, \tag{1}$$

where ε_l – loosening deformation; ε_p – plastic deformation.

The kinetics of dispersed damage accumulation was identified through using the loosening deformation (Lebedev and Chausov, 2004):

$$\varepsilon_l = (1 - 2\mu(\varepsilon)) \cdot \varepsilon, \tag{2}$$

where $\mu(\varepsilon)$ – in-line value of the transverse strain ratio;

$$\mu = -\frac{\varepsilon^t}{\varepsilon}, \tag{3}$$

where ε^t – transverse deformation of the specimen.

3. Results and discussion

3.1. The structure of the steel under investigation

Traditionally, the 17MnSi steel in the as-received state has the ferrite–pearlite microstructure (Aleksandrov et al., 2011; Efimenko et al., 2006). At the same time, at employing various processing regimes of pipe manufacturing it may possess certain differences. The microstructure (or better to say, texture) of the steel under study (Fig. 1a) is stripped one being formed during the rolling process.

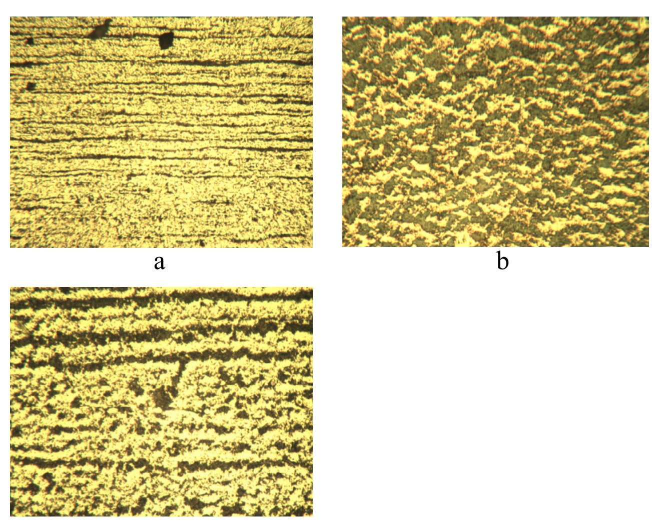

Figure 1 Microstructures of pipe-line 17MnSi steel (×200): a – fine-grained stripped structure; b – coarse-grained structure; c – stripped structure with local segregations.

The width of the ferrite and pearlite stripes is non-constant, and in some regions they have the finite visual dimension. The content of the ferrite makes ~40 %. Coarse material structure is shown in Fig. 1b with a ratio of the ferrite-to-pearlite phase of ~50%. Polygonal ferrite grains have a round shape and might be seen as dark regions without a pronounced spatial orientation. This coarse-grained structure has an increased susceptibility to hydrogen absorption and origin of various defects, especially pores and microcracks (Nykyforchyn et al., 2009). The structure shown in Fig. 1c is similar to that shown in Fig. 1a, but is less uniform with wider stripes of ferrite and pearlite which might be related to less accurate control of thermal treatment conditions during the manufacturing. Metallic inclusions that are presented in the steel are local microdefects and stress concentrators (Efimenko et al., 2006). In doing so at emergence of stresses in a pipe wall they can contribute to the formation of pores within the metal structure, Fig. 1a.

Manifestations of structural anisotropy in the pipe steels are typical for this type of designs. However the revealed anisotropy of the structure can influence both in negative and positive way, for example, it might give rise to increase of the fracture toughness when a crack growth normally to the orientation of the "stripes" (Aleksandrov et al., 2011).

3.2. Complete stress–strain diagrams

To investigate the influence of structural heterogeneity onto the deformation processes in the 17MnSi steel full strain diagrams were employed (Fig. 2). It should be noticed that the high stiffness of the loading system of the upgraded hydraulic ZD-100Pu testing machine under static tension allowed to "sense" peculiarities of deformation process caused by the influence of hydrogen absorption and dispersed damage during the loading and up to the specimen failure. This is of importance for revealing the stage of cleavage crack formation and description of its kinetics when a crack reaches the lateral faces of the specimen (Yasniy et al., 2009).

Let us analyze the obtained results through comparing graphs of material under investigation (Table 1). The curve 1 corresponds to the non-deformed material; the curves 2 and 3 belong to the steels after the certain operating times (Fig. 2). A reduction in the ductility can be treated as the general regularity of the operating effect on the ferrite–pearlite 17MnSi steel. In particular, the value of strain at failure (critical strain) for the non-exploited steel made $\varepsilon_c = 45\%$. The 17MnSi steel of the "Shebelinka – Dykanka – Kiev" main gas pipeline after 38 years of operation has fractured at $\varepsilon_c = 38\%$. The minimum value of elongation $\varepsilon_c = 25\%$ was characteristic feature for the steel cut out from the main gas pipeline "Elets – Dykanka – Kiev" after operation during 31 years (Fig. 2a). This manifests an intensive exhaustion of the material ductility during the exploitation. Increased shape curvature of "stress–strain" diagram confirms the running of degradation processes at the macroscale level. This effect should be taken into account when simulating the behavior of models of the pipeline (Maruschak et al., 2016).

From the physical and mechanical point of view several fundamentally different stages of deformation might be distinguished:

- *Strain hardening section*. It lasts from the onset of the loading and up to reaching the maximum load. This is related to the inconsistencies of structural elements under localized plastic deformation when cleavages in the form of microcracks and micropores are formed; in so doing their dimensions are comparable with the size of structural elements (Aleksandrov et al., 2011). It has been revealed that the yield strength of the non-exploited material makes $\sigma_{YS} = 374$ MPa, while after the operation it was equal to 460 MPa and 470 MPa, respectively (Table 2). It should be noticed that yield strength of 17MnSi steel after the operation has been increased. This indicates less role of relaxation processes under deformation as well as the presence of substantial amount of structural defects [10]. With further loading the number of micro-defects was increased while the rate of their accumulation is reduced due to mutual adaptation of structural elements and their self-organization. It was found that the conventional value of yield strength of the non-exploited material makes $\sigma_{US} = 551$ MPa while for the 17MnSi steel after prolonged operation it is equal to 582 MPa and 615 MPa, respectively (Table 2).
- *The descending section of the diagram*. Particular attention was paid to the study of the kinetics of damage accumulation processes in the 17MnSi steel up to their limit concen-

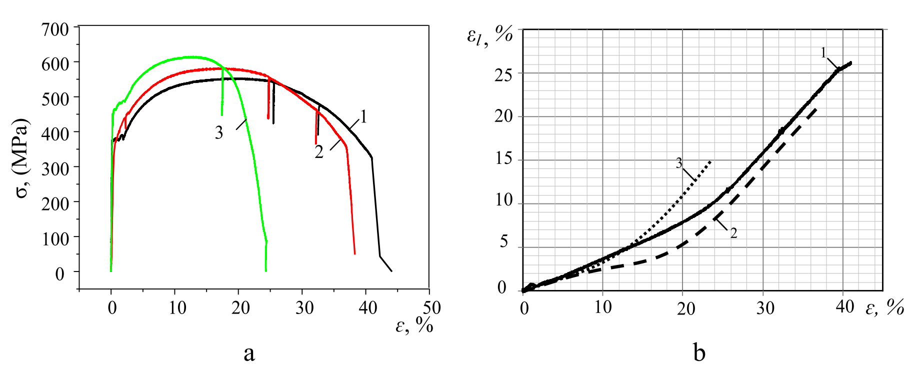

Figure 2 Complete stress–strain diagrams – a and dependence of the loosening strain on the relative deformation – b of the 17MnSi steel specimens under static tension: 1 – as-received state; 2 – the specimen from «Shebelinka – Dykanka – Kiev» pipeline; 3 – the specimen form «Elets – Dykanka – Kiev» pipeline (see Table 1).

Table 2 Mechanical properties of 17MnSi steel after long term operation.

The main pipeline	Mechanical properties		
	Yield point, σ_{YS}, MPa	Ultimate strength, σ_{US}, MPa	Contraction ratio, ψ, %
Steel of reserve (initial state)	375	551	71
«Shebelinka – Dykanka – Kiev»	460	582	67
«Elets – Dykanka – Kiev»	470	615	43

trations and investigation of patterns of their changing to take place at the descending portion of the curve (corresponding to the formation and growth of macro-cracks).

It should be stressed that in the gas pipes the hydrogen is concentrated in the regions of strain localization resulting in reduced crack resistance and material embrittlement. The most sensitive mechanical characteristic which allows evaluating the degradation processes is the relative transverse contraction ($\psi = \Delta A/A_0$ 100%, where ΔA – the change in the cross-section area; A_0 – the cross-section of non-deformed specimen).

The 17MnSi steel in the non-exploited state has the value ψ = 71%, while after the operation it makes ψ = 67% and ψ = 43%, respectively (Table 2). Thus, the long-term operation expectedly results in the reduction of the material ductility (embrittlement) that caused change in the shape of the stress–strain diagram as well as decrease in the relative contraction value of the material (Table 2).

These data emphasize the necessity to consider the influence of the hydrogenation factor on deformation properties of metal pipelines including the formation and growth of micro-defects.

3.3. The diagram of dispersed damage accumulation

The dependence of strain (ε) vs material loosening deformation (ε_l) (Fig. 2b) makes possible to analyze the kinetics of dispersed defect accumulation in the material at various strains. It should be noticed that diagrams of dispersed damage accumulation at stain values up to ε = 10% are almost similar, while substantial differences between them becomes evident at ε > 10%. This testifies for the fact that the coalescence of structural defects (macro-loosening) of 17MnSi steel occurs predominantly at the final deformation stage. An increase in the damage accumulation intensity followed by fracture at ε_l = 15% was observed in this portion of the diagram for the most damaged material among the studied ones, i.e. the steel cut out from the main "Elets – Dykanka – Kiev" gas pipeline.

Unlike the previous case, data on the defect accumulation process in the "Shebelinka – Dykanka – Kiev" main gas pipeline show significant nonuniformity of the deformation distribution. Strain localization in steel specimens of this pipeline steel was revealed at ε = 20%, while for the non-exploited material some later – at ε = 22%. The onset of necking was estimated by the classical method: it was determined through the maximum in the "stress–strain" diagram. It was found that the kinetics of static damages accumulation in the "Shebelinka – Dykanka – Kiev" pipeline steel is very close to the data obtained for the material from the steel taken from the reserve.

However, dispersed defects that occurred in the 17MnSi steel specimens during the operation exert a certain influence onto the maximum damage characteristics. The fracture of the material of the "Shebelinka – Dykanka – Kiev" main gas pipeline took place at ε_l = 22%, while for the non-exploited material loosening deformation reached the value of ε_l = 27%.

4. Conclusions

Long-term operation of ferrite–pearlite 17MnSi steel ambiguously effects its standard mechanical properties. Accumulation of structural damages gives rise to a delay of shear surface formation due to the presence of internal structure defects which increases the strength but reduces the ductility of the material. The generalization of the obtained results evidences on necessity to take into account influence of hydrogen absorption onto main pipelines steel degradation under long-term exploitation.

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