Influence of In-Service Degradation on Strain Localization in Steel of Main Gas Pipelines

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Abstract. General regularities in the failure kinetics of steel of main gas pipelines (17GS) are established using the method of complete stress-strain curves, meanwhile in-service degradation of metals is taken into account. The influence of material degradation on material properties under static tensioning is considered using two independent approaches: the phenomenological model of damage accumulation in metals, and the fractographic analysis method. The accumulation of in-service damage is found to increase a degree of material opening and lead to partial "embrittlement" of the steel matrix due to the microdefects accumulation in the vicinity of metal cracking caused by hydrogenation.

Keywords: strength, deformation, fracture, main gas pipeline, degradation

INTRODUCTION

It is known that after a long-term operation the main pipeline material degrades due to the influence of force (technological pressure, temperature of the transported product, bending moments) and physical and mechanical (hydrogenation) factors [1]. The combination of several degradation factors are the most dangerous, in particular, when the localization of deformation processes in the pipe is caused by subsidence and creep of soil, and peeling of the coating with the activation of hydrogenation processes [2]. It reduces the load-bearing capacity and the crack growth resistance due to the accumulation of structural and mechanical damage in the pipe metal, as well as deformation aging. Nevertheless, most of them, as a rule, have a sufficient reserve of strength and can be operated for a long time, however, the properties of long-operated pipelines need to be clarified, and simple engineering approaches to the evaluation of their condition need to be developed. A great number of works, dedicated to these problems, are known. These works describe two criterion approaches to the evaluation of pipe integrity with technological and in-service defects [3]. The mechanisms of degradation and failure, caused by corrosion factors, are actively investigated [4]. As a rule, such investigations are connected with a combined effect of the soil medium and in-service loadings.

The purpose of this work is to investigate material damage of the main gas pipelines, taking into account its long-term operation.

RESEARCH TECHNIQUE

Fragments of gas pipelines made from steel 17GS 1020 mm in diameter and with the wall thickness of 10 mm were investigated under different terms of operation in the soil (Table 1).

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TABLE 1. Duration of operation of the samples made from steel 17GS cut out of the main gas pipelines

No.	Gas Pipeline	Duration of Operation, years
I	Reserve steel (initial state)	Absent
II	Main gas pipeline Shebelynka–Dikanka–Kiev	38
III	Main gas pipeline Yelets–Dikanka–Kiev	31

The investigations were carried out using cylindrical samples with the sample working section of 5.0 mm. The test was implemented using the updated ZD-100Pu servo-hydraulic setup for static tests with recording the complete stress-strain curve for the material [5]. Cylindrical samples 5.0 mm in diameter were investigated. During the tests, the lateral and longitudinal necking of the sample was recorded using the strain gauges. The fracture surface of the samples was investigated using the REM 106 I scanning microscope.

Total strain was calculated using the approaches presented in [5] as follows:

$$\varepsilon = \varepsilon_p + \varepsilon_n, \qquad (1)$$

where ε_p is the opening strain; ε_n is the plastic strain;

Kinetics of the scattered damage accumulation was determined from the opening strain:

$$\varepsilon_p = (1 - 2\mu(\varepsilon))\varepsilon, \qquad (2)$$

where $\mu(\varepsilon)$ is a current coefficient of the lateral strain; ε is the relative strain;

$$\mu = -\frac{\varepsilon^t}{\varepsilon}, \qquad (3)$$

where ε^t is the lateral strain.

Full stress-strain diagrams. It is necessary to consider the obtained results by comparing stress-strain curves for the material of the pipes made from steel 17GS with a different duration of operation (Fig. 1). Curve I corresponds to the initial material; curves II, III—to the operated material (see Table 1). A general tendency of the operational influence is a decrease in the material plasticity and its hardening, which manifests itself in the increased curvature of the stress-strain curve.

It is known that the development of deformation processes from the yield limit to the failure depends on self-organization of the plastic deformation. A number of regularities are found, in particular, a relationship between the kinetics of the non-uniform strain and a graded nature of complete stress-strain curves is established:

– within the stage (0–1), the material deforms in the elastic manner;

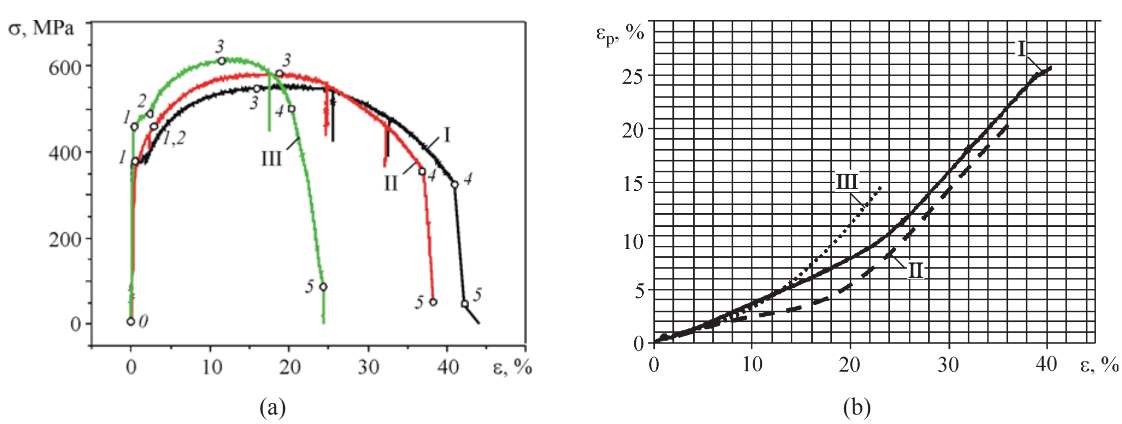

FIGURE 1. Static stress-strain curves for steel 17GS (a) and dependence of the opening strain on the residual strain of the sample (b) (designations I, II, III correspond to the data of Table 1)

– within the stage (1–2), the redistribution of macrodeformation sections takes place; it is known from the literature [6] that this section is characterized by auto-wave deformation processes;

– within the stage (2–3), a coordinated deformation of the material with structural and mechanical defects occurs; this stage of parabolic hardening is characterized by self-organization of the deformation sections of the process localization;

– within the stage (3–4), a neck forms, and there is a transition from the "stationary" system of the localized deformation to the macrolocalization and the neck formation;

– within the stage (4–5), the accumulation of macrodamage occurs (coalescence of pores into the macrocrack) with the sample failure.

A shape of the descending section is a manifestation of the "neck formation"; moreover, it characterizes the static fracture toughness of the metal. Its shape allows evaluating the availability of degradation processes at the macrolevel, the influence of which should be taken into account in the material deformation models. The experimental data prove that the long-term operation causes a noticeable decrease in general steel plasticity from 42% (sample I) to 38% (sample II), and 25% (sample III) with a simultaneous increase in the strength properties of steel 17GS, which bears a bright testimony to the exhaustion of its plasticity.

In order to investigate the influence of structural non-uniformity on the deformation processes in steel 17GS, the dependence ε–ε_p is used (Fig. 1(b)). The degradation processes, which occur in the operated material, change the kinetics of the damage accumulation process appreciably. First of all, it affects the pore coalescence stage and the ultimate damage of the material.

Apart from the accumulation of structural defects and pores, the long-term operation causes a partial "embrittlement" of the material matrix. It is experimentally confirmed by a significant reduction in plastic properties of the material and is noticeable on the dependence ε–ε_p, where the opening increases in the operated material much more quickly, however, the ultimate value ε_{pc} is 1.16 times (sample II) and 1.75 times (sample III) less than that of the metal in the initial state (sample I) (Fig. 1(b).

DISCUSSION

Nucleation and coalescence of the defects can be considered from the viewpoint of the evolution of deformation scale levels and a shear stability loss. Each curve is considered as a totality of the deformation process self-organization sections, moreover, the graded nature of the process transfers to a higher level in the characteristic points (bifurcation points). The failure is considered as a macroscale loss of the material stability at the macrolevel. As it is seen from the data of the opening strain variation curves, the material is a non-uniform medium (matrix + pores), moreover, the shape variation of pores and matrix deformations are the informative indicators of the material degradation and, correspondingly, of the resistance to brittle cracking and hydrogen cracking. It is experimentally proved that the plastic deformation of the main gas pipeline steel in initial state takes place gradually.

Micromechanisms of the deformation are realized within the section (0–2), Fig. 1(a), where the material damage is the lowest, since the working sample cross-section has a sufficient reserve of the load-bearing capacity, and the material actively resists the deformation and failure [7]. Further change of the curve slope angle depicts not only the effect of the initial damage, but also a decrease in its resistance to shear deformations during loading. Regardless of the microstress type, the interconnection between deformation processes in the adjacent sections spreads to a higher scale level. Strain localization in the loaded sample manifests itself in the kink of the curve and a transition to the plastic deformation at different scale levels.

Mesolevel allows describing the graded nature of the "stable" deformation and characterizes the material resistance to failure, without the localization of macrodefects, section (2–3), Fig. 1(a). Analysis of the dependence ε–ε_p, Fig. 1(b), testifies to the fact that the structural adaptation of the material takes place due to the pore shape variation, and the deformation of metal sections is adjacent to pores [8].

Section (3–5) is a transition from the "stable deformation" to the unstable stage. It characterizes the exhaustion of the material plasticity and its crack growth resistance [2]. The obtained results are important for damage analysis of the main gas- and oil pipeline systems. Their practical value consists in the fact that they can be used successfully for the evaluation of the material damage and the ultimate state of the main gas pipeline materials [9]. The advantage of the proposed methods, in comparison with the well-known methods, is the possibility of taking into account the "entire" resource of material plasticity, in particular, at the pre-failure stage, which creates physical preconditions for more precise evaluation of the objects designed for a long-term operation.

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CONCLUSION

The methods of mechanical testing and evaluating the conditions of metallic materials are developed. The methods are based on the construction of the complete stress-strain curves, the quantitative damage calculation of steel 17GS after a long-term operation.

The connection between the damage accumulation and the variation of properties of the main gas pipeline material in initial state and in-service state is demonstrated. The dependence between the material damage and the variation of structurally sensitive parameters, measured by different instrumental methods, is established.

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