Condition evaluation of steel X65 in one of the sections of "Soyuz" gas main after long-term operation

Hodnocení stavu oceli X65 na části plynovodu "Sojuz" po dlouhodobém provozu

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The basic regularities in deformation and fracture of pipe steel X65 are revealed by testing specimens from the pipe fragment cut during the repair of the "Soyuz" gas main after 30 years of operation. It is shown that the pipe steel slightly changes its properties when the gas main is operated under the influence of working stresses and environmental factors. Structural degradation and micro-defects accumulated in the pipe wall were scattered, indicating that the material retains sufficient plasticity that allows it to resist fracture processes and the nucleation of macrocracks.

Základní trendy v deformaci a porušení trubkové oceli X65 by zkoumány testováním vzorků z části trubky vyřezané během opravyplynovodu „Sojuz" po 30 letech provozu. Je ukázáno, že vlastnosti oceli se lehce změnily, když plynovod byl provozován pod vlivem mechanických pnutí a vlivu prostředí. Strukturní degradace a mikrodefekty naakumulované ve stěně trubky byly rozptýleny, což dokazuje, že materiál si zachovává dostatečnou plasticitu, která umožňuje odolávat lomu a zárodkům makrotrhlin.

INTRODUCTION

It is known that after the operation of gas mains for more than 30 years, the hardness and relative reduction of the steel decrease, but the variance of strength properties increases [1,2]. Pipe steels harden due to the exhaustion of their plasticity and the accumulation of structural defects. An ambiguous change in the plasticity characteristics of the long-operated pipe steel takes place, i.e. the relative reduction decreases and the relative elongation increases [3,4].

However, some works are known [5], the results of which indicate that structural degradation almost does not affect the mechanical properties of the pipe material, although the long-term operation leads to the redistribution of cementite, and hydrogenation causes a slight decarbonisation of the material. The deformation aging of such steels is negligible and is manifested by the release of fine dispersed carbides in the volume of grains, which cause a decrease in the impact strength [5].

Significant differences in the mechanisms of steel fracture of gas mains in the initial and long-operated states are due to a variety of their operational damage types [6,7]. Consequently, the existing approaches to their fractional diagnosis require improvement and concretization. In addition, studying the defects of the long-operated pipe steels is the basis for the creation of high strength steels with different types of microstructure. It should be noted that the systematization of the operational damage is an important scientific and engineering task, and its description requires further research [8].

The purpose of this research is to analyze the metal condition of the "Soyuz" gas main after a long-term operation and to identify the impact of the accumulated structural defects on its load-bearing capacity and crack resistance.

RESEARCH TECHNIQUE

In order to analyze the degradation mechanisms of the "Soyuz" gas main with a diameter of 1420 mm and a wall thickness of 16 mm, a comprehensive study of its fragment cut out during scheduled repairs was performed at the station "Gusiatyn" (the village of Sukhodil) of the Ternopil region.

The kinetics of deformation and fracture of specimens were investigated by the method of complete stress-strain diagrams (Fig. 1). This allowed providing such test conditions, in which it is possible to assess the stage-like nature of the deformation and fracture processes at various stages, in particular, during macrofracture [9]. Cylindrical specimens with a diameter of 5 mm and a working section of 25 mm were used. They were tested on an upgraded hydraulic installation ZD-100Pu for the static tests. The modified version of the installation consists of two contours - the external (loading frame of the test machine) and the internal ones, which allowed building complete stress-strain diagrams.

The static crack resistance of steel was estimated by the parameter K_λ, which is based on the concept of complete stress-strain diagrams of plastic materials and was proposed by prof. M.G. Chausov as an express-method for evaluating fracture toughness.

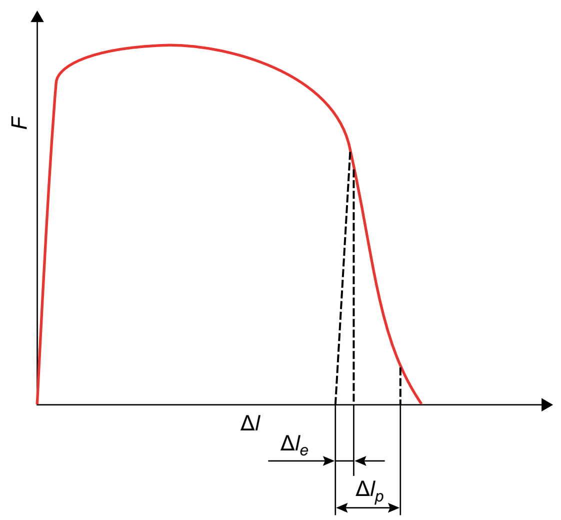

Fig. 1. Primary complete stress-strain diagram of plastic materials
Obr. 1. Primární tahový diagram plastických materiálů

This method was previously theoretically and experimentally substantiated by professors A.O. Lebedev and M.G. Chausov and provides for the stability of deformation and fracture processes, in particular, at the stage of macrofracture [9, 10]. They were also the first to develop a new criterion of crack resistance K_λ based on the analysis of complete stress-strain diagrams.

$$K_\lambda = \sqrt{S_\kappa \cdot \overline{\Delta l_p} \cdot E},\ [\mathrm{MPa}\sqrt{\mathrm{m}}] \quad (1)$$

where S_k is the actual resistance of the material to tearing material; Δl_p is the specimen elongation at the growth stage of the separating macrocrack normalized to the cross-sectional area of the standard specimen; E is the Young's modulus of materials.

After mechanical tests, a visual analysis of specimen fractures was performed along with the metallographic research on the microscope AXIOVERT 40-MAT. The specimens were deformed to a certain level, or they were cut in longitudinal and transverse directions to fracture, so that one of the cut-off planes became an axial section after grinding and polishing. This technique made it possible to study the mechanisms of nucleation and propagation of the macrocrack on a microscope along the width of the specimen. These studies were aimed at evaluating the possibility to inhibit macrocracks by structural elements of the material, as well as detect and systematize structural distortions in the vicinity of the crack tip of static fracture. Specimens in the breakage zone were ground and polished with diamond paste at the USHPO-0 installation, gradually reducing the grain size. After that, the prepared surface of the slurry was etched in 4.0% solution of picric acid in ethyl alcohol.

Complete stress-strain diagram

A complete stress-strain diagram was constructed. It was found that the X65 steel has sufficient strength and plasticity at the macro level (Fig. 2). This is evident because the diagram is sufficiently long, that is, the plasticity of the material allows it to accumulate microstructural defects and microcracks on a sufficiently large area.

This indicates the accumulation of insignificant scattered structural damage, which slightly affects the variation of the mechanical properties of the pipe steel of the gas main. Several unloadings were made on the descending area, which allowed detecting the degradation of the elastic modulus as a result of accumulation of structural defects and pores.

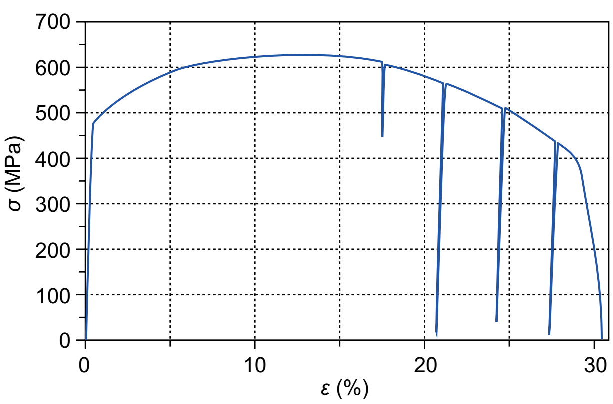

Fig. 2. Complete stress-strain diagram of exploited steel X65 of the Soyuz gas main
Obr. 2. Tahový diagram pozorované oceli X65 z plynovodu Sojuz

Tab. 1. Mechanical characteristics of steel X65 of the Soyuz gas main in the initial and exploited states / *Mechanické charakteristiky oceli X65 v původním stavu a po expozici*

Gas main pipeline	**Manufacturer of pipes, standard**	**Outer diameter of pipe, mm**	**Normative characteristics of steel**		
			Steel	**σ_{us} (MPa)**	**σ_{ys}, (MPa)**
«Soyuz», CS "Gusiatyn" (initial state)	Japan, TU-1975	1420	X65	654	561
Exploited state				626	500

Tab. 2. Parameters of crack resistance K_λ and K_{IC} for steel X65 after a long-term operation / *Parametry náchylnosti k praskání pro ocel X65 po dlouhodobém provozu*

Steel	**Experimental data**			**Results of calculations**	
	Δl_p (mm)	**F_k (kN)**	**E (GPa)**	**K_λ (MPa)**	**K_{IC} (MPa)**
X65	0.364	6.975	1.7	483.9	111.3

Compared to the initial material, the conditional limit of strength decreased by 4.3%, and the yield strength by 11%, Table. 1.

The specific work of fracture A_p was taken as the parameter for assessing damage and static crack resistance of the material [9, 10]:

$$A_p = \frac{F \cdot \Delta l_p}{S^2} = \frac{6.957 \cdot 0.364}{5.725^2} = 0.0774631 \text{ [kN·mm}^3\text{]}$$

and parameter of crack resistance K_λ was calculated and summarized in Table 2.

$$K_\lambda = \sqrt{S_0 A_p E} = \sqrt{17.78622 \cdot 0.0774631 \cdot 1.7 \cdot 10^2} =$$

$$= 15.3043 \text{ [kN·mm}^{3/2}\text{]} = 483.9 \text{ [MPa}\sqrt{m}\text{]}$$

The performed calculations of crack resistance, taking into account the formation and accumulation of structural defects, are the basis for refining the estimation of the strength and crack resistence of the pipe wall and predicting possible fracture. However, the obtained phenomenological models of deformation and fracture need to be supplemented with the data of metallographic research. This will provide for the generalization of the obtained physical and mechanical patterns in the variation of microstructure and their influence on the deformation and strength properties of the exploited steel.

Metallographic analysis

Metallographic investigations of the steel of the gas main revealed that steel X65 has a ferrite-perlite structure, there are some stripes obtained as a result of controlled rolling (Fig. 3a,b). In the macroanalysis of the trenches of the destroyed specimens of the exploited steel, numerous pores and separate microcracks were found in the zone of fracture. This indicates the localization of the deformation process, as well as the coherent impact of the separation and tear mechanisms. In the vicinity of the lateral surfaces of the specimen neck were identified zones of structural heterogeneity, which may have been sections of the specimen delamination. Fragmentation and deformation of the structure were revealed along with the occurrence of local delaminations, indicating a significant energy dissipation during the propagation of the macrocrack (Fig. 3c,d).

A high degree of disorientation of the material structure in the vicinity of the crack front is evidenced by metallographic images. The lack of clarity and "blurriness" of the structural components is due to the deformation localization and significant deformation in the zone of the specimen fracture, indicating its high plasticity. It is noticeable that macro- and microfracture of the exploited steel X65 is ductile in general and was accompanied by significant plastic deformation. Both in the initial and exploited states, the steel was destroyed by the typical ductile mechanism of nucleation, coalescence and growth of cavities due to the elongation of interstices between cavities to rupture. At the same time, against the background of the dimple-like relief, we found the breakage texture in the exploited steel, which is associated with the rolling direction of the pipe steel. Defects in the form of stratifications oriented along the same direction were found on breakages. Such stratifications, in our opinion, were the result of the formation of scattered damage under the influence of rigid force conditions of the long-term exploitation of the steel in the gas main (Fig. 3c,d). They were formed due to the weakening of the bonds between the structural components of the steel across the pipe wall, making it easier to separate them [11]. In the image presented in Figure 3e,f, it is noticeable that the breakage has deformed grains, as well as the grains that fell into the zone of polishing the pores and cracks, which clearly illustrates a decrease in the deformation resistance of the material during the growth of a macrodefect. The deformed elements of the steel structure indicate relaxation processes in the specimen neck with a significant increase in macrodeformation [12]. Physical mechanisms of the specimen fracture are associated with the formation and propagation of a system of multiple microdefects and fracture of structural elements. In this sense, the resulting images contain an integral picture of the damage accumulation and the

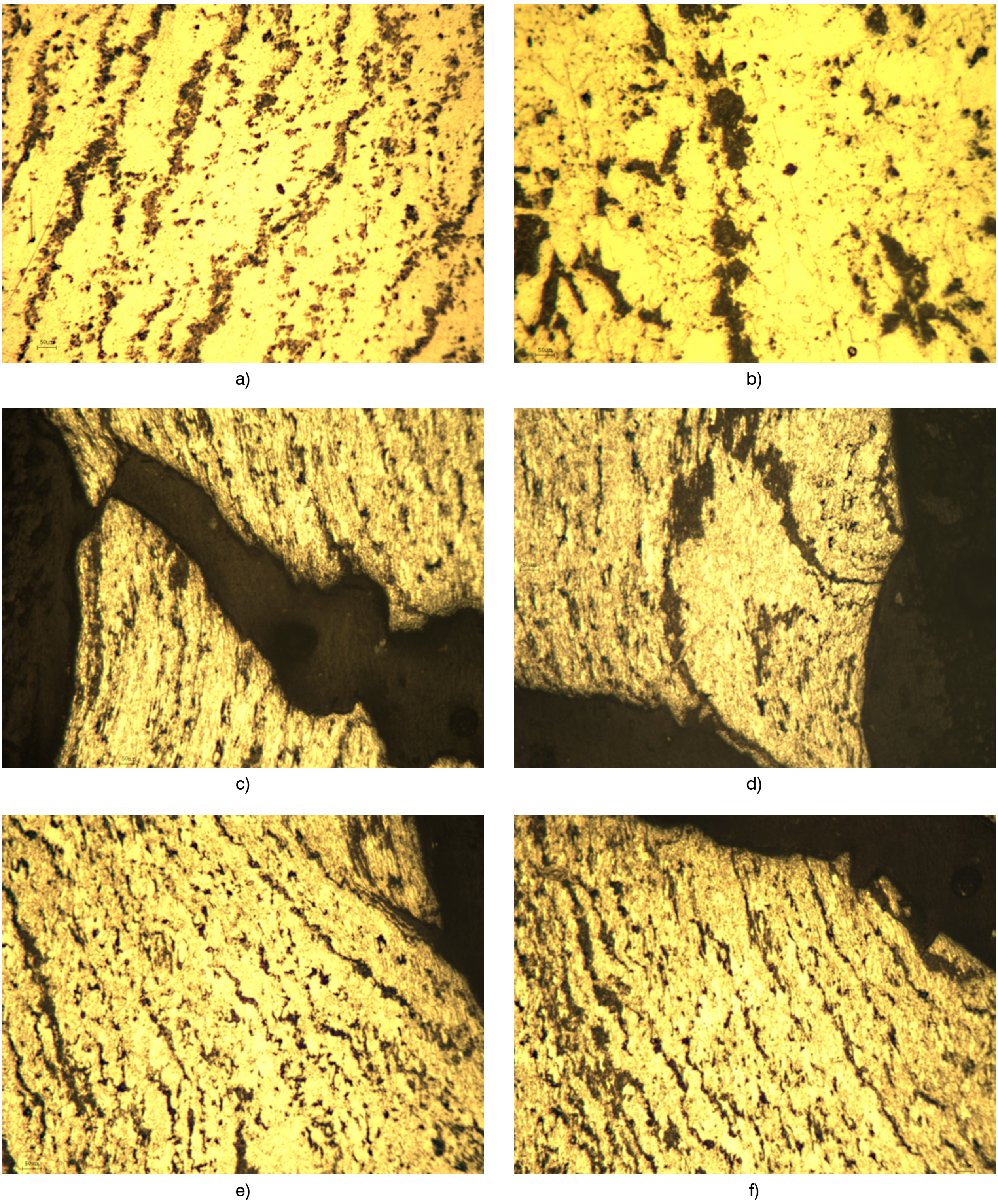

Fig. 3. Structure of steel X65 after 30 years of operation of the Soyuz gas main: a), b) in the non-deformed and c) – f) deformed states (×400)
Obr. 3. Struktura oceli X65 po 30 letech provozu na plynovodu

conditions for macrofracture of the specimen. It should be noted that the analyzed pipe steel contains a number of microdefects and scattered damage, however, they slightly affect the mechanical properties of the material, which has a satisfactory load-bearing capacity and crack resistance, as evidenced by experimens. Thus, the processes of deformation and fracture of the exploited material are described in this paper, and the mechanisms of accumulation of structural defects are generalized based on the use of the method of complete stress-strain diagrams and metallographic analysis.

Long-term exploitation of Ukrainian gas transmission system leads to degradation of main gas pipelines metal properties, change of its structural state due to stress influence, corrosion environment and hydrogen. At the same time, the degree of metal's damage differs on different gas pipelines. Results obtained in this article allow saying that part of the gas pipelines is in a satisfactory condition and their metal damage is insignificant. This allows continuing their exploitation after carrying out procedures of non-destructive testing and regulatory repair works.

CONCLUSIONS

The basic regularities in deformation and fracture of pipe steel X65 are revealed by testing specimens from the pipe fragment cut during the repair of the "Soyuz" gas main after 30 years of operation. It is shown that the pipe steel slightly changes its properties when the gas main is operated under the influence of working stresses and environmental factors. Structural degradation and micro-defects accumulated in the pipe wall were scattered, indicating that the material retains sufficient plasticity that allows it to resist fracture processes and the nucleation of macrocracks.

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