ASSESSMENT OF RESIDUAL LIFE OF MAIN GAS PIPE-LINES WITH CORROSION-FATIGUE DAMAGES

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Methods for complex assessment of the residual life time of main gas pipe-lines after long-term operation are analyzed. They use a calculation, based on static strength, low cycle fatigue and fatigue crack growth resistance criteria. Loading conditions and actual technical state of the pipe-line (in particular, the presence of defects and damages) as well as the material ageing and corrosion effects are very important. The specific features of these factors effect in large-scale tests, laboratory investigations and pipe-lines calculations are considered.

INTRODUCTION

It is very important for many branches of industry and public services that the gas-transport systems work regularly. The accidents on the pipe-lines are very dangerous not only because of the gas losses, but also of the industrial equipment damages, failure of municipal objects and environment pollution. Therefore, the problem of ensuring the high reliability of gas pipe-lines has been paid much attention to. It is especially urgent for the pipe-lines, operating for a long time, first of all for those, that have reached the end of their design life. The pipe-line ageing increases the danger of its failure due to development of corrosion and fatigue damages. However, construction of new production lines is very expensive and needs much time. The analysis shows that in most cases, the underground pipe-lines even after 30-40 years in service can be further employed, provided that regular checking of the technical state and evaluation of the residual life of the pipe-lines is carried out, using, in particular, the estimates calculation of the residual strength and life time. In its turn, this presupposes a substantial extension and supplement of the traditional methods for the gas pipe-lines strength calculations in order to consider more completely the time, which is a factor, that reduces serviceability of a pipe-line. This factor is related with the processes of fatigue, corrosion and ageing of

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materials in service conditions.

The modern methods of corrosion-fatigue fracture mechanics allow the diagnostics of these processes development and, hence, the evaluation of the residual life of structures. The present paper has been undertaken with the aim to analyze the specific features of utilization of the above approach within the framework of the basic criteria, that consider the main mechanisms of the strength decrease of the material in a pipe of the main pipe-lines.

ASSESSMENT OF SERVICEABILITY IN TERMS OF A STATIC STRENGTH CRITERION

According to the current Standard (1, 2), the main criterion for the pipe-line strength estimation is the condition of static strength. Stresses in a pipe wall σ should not exceed the admissible value R for the pipe material

$$\sigma \leq R \quad (1)$$

For the gas pipe-lines, the value of σ is assumed equal to the circular stresses, caused by the gas service pressure p ($\sigma = pD/2s$, where D is the internal diameter of a pipe, s is a wall thickness), and the value of R is established from the ultimate strength of the material and safety margin, which is chosen with respect to the type and service conditions of the gas pipe-line. Criterion (1) is the basic one in design calculations and, particularly, in selecting the material of pipes and their dimensions. Its application for the pipe-lines, that have been operating for a long time, require some amendments, in order to take into consideration the temporal variation of the calculational parameters as compared with their original values. These variations are conditioned by the following two factors.

Firstly, the degradation of material can cause the decrease of the strength characteristics of material, that is, a corresponding decrease of R value. The degradation level can be established by testing the standard specimens, cut out of the gas pipe-line material under study, or can be approximately evaluated by correlation dependences of the mechanical characteristics of the material and its hardness or some other parameters that can be assessed by NDT methods.

Secondly, the processes of corrosion and wear in the material can cause the pipe wall thickness decrease, and, consequently, the increase of the operating stress value σ. For the underground main pipe-lines, the corrosion of the external pipe surface in the sites of insulation disturbance or poor cathodic protection in the regions of high corrosive soil, is the most dangerous factor. Standard methods can be used for defining the intensity of the corrosion processes: for example, long-term investigations of the specimens, placed into the soil with the given properties (structure, chemical composition, humidity, temperature etc.). For a rapid engineering assessment, the correlation dependences that relate the corrosion wear rate u and specific electric resistance of soil ρ are most frequently used. According to data of Stryzhevsky (3), the corrosion influence of soil is insignificant at ρ exceeding 100 Ohm $\times$ m, and it can be neglected. At the values of ρ = 30 ÷ 40 Ohm × m the corrosion activity of soil is high (u= 0.02 ÷ 0.14 mm/year), while at ρ < 30 Ohm × m it is very high. However, the drawbacks of such a one-sided evaluation are evident. This estimate does not show the complex character of corrosion processes during interaction of a metal with a soil. Some new results, concerning the above, have been received by Zubyk (4). He analyzed the influence of the main factors of corrosion activity of various soils and determined the conditions for optimal modelling of their properties by electrolytes in laboratory tests, concerning assessment of the corrosion rate of pipe steels.

Besides, it is known, that corrosion processes are enhanced by mechanical stresses action. Hutman et al. (5) propose that this action can be written as a linear dependence:

$$u = u_0\left(1 + k\sigma_0\right) \tag{2}$$

where u, u_0 is the corrosion rate in the loaded and unloaded material, respectively; σ_0 is a hydrostatic compound of stress tensor; k is a constant (for pipe steels k = 0.04 Mpa^{-1}). The proposed dependences are the main ones for the assessment of corrosion rate in a pipe wall.

The account of the above two factors allows to predict the pipe-line original safety margin and evaluate residual life as a time for reaching the critical state (in a sense of criterion (1)).

ASSESSMENT OF THE RESIDUAL LIFE BY A LOW-CYCLE FATIGUE CRITERION

During operation, the main pipe-lines are subjected to the effect of repeated static loads: the service pressure at the outlet of compressor stations changes with variation of the efficiency and transfer conditions; the gas pipe-lines are regularly disconnected in order to carry out scheduled checking, remove the damages etc. The average number of such changes during a conventional service life of the pipe-line (30 years) is 0.8 ÷ 1.2×10^4 cycles. For the definite sections of the gas pipe-lines, depending on their state and functioning capacity, a number of cycles can substantially exceed the mentioned value (or it can be exhaused for a shorter period of time). All this attests to the fact that an assessment of the gas pipe-line serviceability should be conducted from the positions of low-cycle fatigue. The principles of performing such calculation are given in methodical recommendations (1, 6). Durability assessment uses the basic curves of low-cycle fatigue of materials in coordinates: the plastic deformation amplitude (ε_p) - loading cycle number to fracture (or macrocrack initiation) (N_*).

In its turn, for determination of the local field of elastoplastic deformations in the process zone, we use curves of the material cyclic deformation ($\varepsilon_p - N_*$) and the approximate Neuber-type dependences ($k_\sigma k_\varepsilon = \alpha^2$), where α is a theoretical coefficient of stress concentration; k_σ, k_ε are virtual concentration coefficients of elastoplastic stresses and deformations, respectively.

The calculation according to this model allows the prediction of the residual life of a pipe-line, accounting the processes of fatigue crack initiation at the stress concentrators (especially those related with the welded joints), defects and damages, like hollows, scratches, corrosion cavities etc. However, these calculations should additionally account the processes of corrosion and ageing of metal in case of undergraund pipe-lines after a long time of operation. The influence of the mentioned two factors can be very significant. In particular, the assessment of the low-cycle fatigue curves by the material mechanical characteristics shows, that after 25 years of operation, the period of crack initiation can be $3 \div 4$ fold shorter than in the original material in similar loading conditions. In the high corrosive soils (for example, marshy, clay soils with sulphate reducing bacteria) the process of fatigue fracture can be accelerated by 3 times. Besides, the important direction in improving the calculational methods and getting the more reliable results is the development of the calculational models. The latter consider the common influence of the corrosion electrochemical processes and development of mechanical damages under fatigue fracture at repeated-static loading and environment effect.

ASSESSMENT OF THE RESIDUAL LIFE BY A CRACK GROWTH RESISTANCE CRITERION

Development of corrosion-fatigue cracks is the cause of about 1/3 accidents on gas pipe-lines. If the service life time increases then their number grows. In this connection, the ensuring of the required level of the material crack growth resistance is a necessary condition of the safe operation of the pipe-line and increase of its life time. Within the framework of the linear fatigue fracture mechanics (see, a reference edited by Panasyuk (7)), the life of a structural member with a crack-like defect is obtained from a relation

$$N_* = \int_{l_0}^{l_*} \frac{dl}{F(\Delta K_I)}, \tag{3}$$

where N_* is a period (a number of loading cycles) of crack length increment from the initial l_0 to the critical l_* size; $F(\Delta K_I) = dl/dN$ is a dependence of crack growth rate on the stress intensity factor range per a cycle ΔK_I, which is defined by the kinetic fatigue fracture curve for a given material and loading conditions. The value of ΔK_I for the defect of a given geometry and dimensions is calculated by solving an appropriate problem of elasticity theory; for most typical defects such solutions are available in reference books, e.g. (7).

In the gas pipe-lines assessment the following factors are very important (they can greatly influence the fatigue crack growth).

Plastic behaviour of material

The gas pipe-lines are constructed from rather ductile steels, fracture of which is accompanied with a pronounced plastic deformation. In most cases, the condition of small plastic zones sizes is disturbed during fatigue crack growth. As a result, the linear fracture mechanics can not be applied in evaluations. It is possible to perform calculations within the framework of deformation approach, using the generalized δ_c-model. For this purpose, the kinetic diagrams of fatigue fracture are presented as a crack growth rate vs. crack tip opening displacement $\Delta\delta$. The use of the δ_c-model opens wide prospects for modelling the processes of the elastoplastic deformation of material, including the crack closure effects. This improves the prediction ability and accuracy of calculations of the corrosion-fatigue crack growth rates in different loading conditions, as shown for example, in papers of Panasyuk and Andreykiv (8).

The effect of corrosive environment

As in low-cycle fatigue, corrosive environments (soils), are the factor that significantly influences the fatigue crack growth resistance of the material. This effect can be established by experiments, using the plots of kinetic diagrams of corrosion-fatigue fracture. For this purpose the standard notched specimens under cyclic loading and corrosive environment effect have been tested. In these investigations crack growth rate, on the one hand, and the stress-strain state parameters and the characteristics of the physicochemical situation at the crack tip, on the other hand, are checked (Romaniv and Nykyforchyn (9)). In laboratory conditions it is practically impossible to model all the possible combinations of the metal-environment-loading conditions, which occur during operation of the gas pipe-lines. Therefore, the development and application of calculational models is of great importance. They allow the prediction of the corrosion-fatigue crack growth rate under various conditions, using the results of the basic experiment (Panasyuk et al (10)). Finally, when conducting calculations, it is necessary to take into consideration not only the intensifying effect of corrosion environment on fatigue crack growth rate, but also the influence of stress corrosion. The actual fracture of gas pipe-lines is evidently a combination of the both mentioned mechanisms.

Material ageing

Degradation of material in operation is most brightly expressed by a decrease of the plastic properties - the material embrittlement occurs. Therefore, the significant reduction of the fatigue and static crack growth resistance characteristics is expected. According to the obtained data, the $2 \div 3$ fold increase of fatigue crack growth rate due to ageing is observed. The process of degradation is substantially affected by corrosion. Besides, it unevenly develops along the pipe wall. This fact should be taken into account, when analyzing the crack growth.

CONCLUSIONS

The low-cycle fatigue, static strength and fatigue crack growth resistance criteria define the most typical mechanisms of the main gas pipe-line fracture, observed in practice. The ability of these criteria to predict fracture is greatly improved when the material ageing and corrosion effect are taken into account. The carried out calculation, based on the above criteria, alongside with the data of large-scale testing can provide an objective assessment of the actual technical state and possible life time of the pipe-lines. These results can be successfully used for grounding the admissible service life of gas pipe-lines, prediction of the optimal terms and required amount of the repair works, development of the system of the preventing measures to locate in due time the dangerous defects and then to remove them. These results allow also to solve some other applied problems, related with ensuring the reliable and effective operation of gas-transport pipe-lines.

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