

EVALUATION OF THE RESIDUAL SERVICE LIFE OF STRUCTURAL ELEMENTS IN HYDROGEN-CONTAINING MEDIA

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We propose an algorithm for the evaluation of the residual service life of structural elements with cracks (hydrogen-fueled engines and petroleum-hydrocracking reactors) under the combined action of hydrogen-containing media and long-term mechanical loads.

Keywords: residual service life, crack, hydrogen, mechanical load.

Introduction. The problem of evaluation and prediction of the serviceability of structural elements intended for long-term operation under conditions of complex multiple-mode thermal and force loading combined with the action of hydrogen-containing media is connected with the formation of hydrogen-induced cracks. For these structures, it is insufficient to perform calculations for a single operating mode regarded, for some reasons, as the most dangerous. To guarantee the reliability of predictions of serviceability, it is necessary to analyze the entire history of interaction with hydrogen and the changes in the temperature and stress-strain (SSS) states of the structure for all modes of cyclic loading: startup – nominal mode – shutdown (scheduled or emergency). This is explained by the fact that the catastrophic combination of the action of external factors and factors of hydrogen degradation of metals can be encountered in all stages.

Algorithm of the Analysis of Structural Elements for Long-Term Strength in the Stage of Hydrogen-Induced Subcritical Crack Growth in Metals. The strength analysis and evaluation of the service life of structures under conditions of complex multiple-mode thermal and force loading combined with the interaction with hydrogen-containing media includes the following stages:

- (i) analysis of the operating conditions of a structure and possible causes of its fracture;
- (ii) analysis of changes in the temperature field and redistribution of hydrogen in the most dangerous sections of the structure for each operating mode;
- (iii) investigation of the stress–strain state in the vicinity of a defect and determination of the parameters characterizing this state: stress intensity factors (SIF), crack opening displacement, etc.;
- (iv) experimental evaluation of the characteristics of crack resistance of the material in hydrogen;
- (v) investigation of the kinetics of fracture processes, i.e., of the subcritical crack growth in hydrogen-containing media, and evaluation of the residual service life of the analyzed structure on the basis of the accumulated data.

The aim of the first stage is to obtain the data on the specific features of loading of the material in the structure and its interaction with hydrogen-containing media required for the subsequent numerical analysis. The hydrogen-affected zones, i.e., the regions of contact of hydrogen with the metal, are determined in structural elements on the basis of the data on the working processes and loading modes (mechanical loads, temperature fields, the presence of hydrogen, and the parameters of the medium) combined with the information on the sensitivity of the material to the influence of hydrogen for the parameters (temperature and the degree of activity of hydrogen) characterized by the presence of various forms of hydrogen-induced degradation. In this case, to predict the resistance of structures to the action of hydrogen under conditions of multiple-mode thermal and force loading, it is necessary to know not only the unfavorable combinations of the indicated parameters that can be attained for the entire analyzed period but also the regularities of the behavior of these parameters as functions of time.

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The initial data must also contain the data on defects existing in the structure, namely, their location, shape, sizes, etc. The corresponding parameters are determined either as a result of detection of defects by the existing methods of monitoring or on the basis of the data on typical defects.

In numerical calculations, it is necessary to take into account the fact that the structure may contain defects not detected in the process of monitoring. In this case, as a rule, it is assumed that the structure contains a defect of the most dangerous type, namely, a crack located in the hydrogen-affected zone with the most unfavorable orientation relative to the acting loads and from the viewpoint of the properties of materials and other factors.

The data obtained in the first stage are used as basic in the computational scheme according to which the evaluation of strength and residual service life of structures is reduced to the solution of a model problem (or a series of problems) of limiting equilibrium state and the kinetics of development of the initial defect in the investigated structural element under given conditions of its loading.

In the second stage, we determine the behavior of the temperature field, propose a model and study the processes of accumulation and redistribution of hydrogen in the metal in the most dangerous sections of the structure for each operating mode. This is explained by the necessity of investigation of the process of formation of zones supersaturated with hydrogen and dangerous from the viewpoint of the possibility of formation of hydrogen-induced defects (cracks) in structural elements. Investigations of this sort must include the successive solution of the problems of heat conduction and then the problems of diffusion of hydrogen under the corresponding conditions.

In the third stage, it is necessary to study the SSS in the vicinity of the defect and determine the design-basis parameters specifying this state, namely, the SIF, crack opening displacement, etc. Problems of this sort are quite complicated from the mathematical point of view, especially in the three-dimensional statement. Thus, closed solutions for the evaluation of the crack-tip opening displacement δ were obtained only for some simple configurations of cracks in infinite bodies [1, 2]. The methods based on the determination of the SIF are used much more extensively. The most complete survey of the results obtained in this direction can be found in [3].

The fourth stage is connected with the experimental investigation of the characteristics of crack resistance of the material in hydrogen-containing media. In fracture mechanics, there are numerous procedures applicable for the realization of this stage.

Assume that l_i is the characteristic linear size of the initial defect determined by the methods of nondestructive testing and that the SIF for this defect is known. Then, on the basis of the data on the crack resistance of the material, we determine the ultimate sizes of the crack [2], i.e.,

the ultimate size l_0 of a crack that does not grow under the operating load, i.e., the condition $K_I(l_0) = K_{Ith}^{(H)}$ is satisfied;

the critical size of the crack l_c corresponding to the onset of its catastrophic propagation, i.e., the condition $K_I(l_c) = K_{Ic}$ is satisfied.

Cracks whose sizes l_i belong to the interval $l_0 < l_i < l_c$ can grow under the specified operating conditions. For these cracks, the process of crack growth determines the residual service life of a structural element obtained from the solution of the equation

$$\frac{dl}{dt} = v(K_I, C_H), \quad (1)$$

where v is the crack growth rate.

Thus, the fifth stage is devoted to the investigation of the kinetics of fracture, i.e., the processes of subcritical crack growth in hydrogen-containing media, and the evaluation of the residual service life of structures on the basis of the data of these investigations.

Clearly, it is preferable to construct the corresponding kinetic diagrams as a result of the experimental investigation of materials for the parameters of interaction with hydrogen reproducing the actual operating conditions. However, the available data on the kinetics of hydrogen-assisted crack growth in metals and the possibilities of their accumulation are limited. This is why, in numerous practical cases, the sets of experimental characteristics of crack resistance required for numerical calculations are either absent or insufficiently complete for the specified ranges of operating parameters. In these cases, it is necessary to use theoretical approaches.

Evaluation of the Crack-Growth Rate under the Action of Hydrogen and Long-Term Static Loads.

Consider an elastoplastic isotropic plate containing a macrocrack of length l subjected to the action of tensile stresses p and a hydrogen-containing medium with concentration of hydrogen equal to C_S in the vicinity of the crack tip.

According to the experimental data [2], the process of growth of a macrocrack in hydrogen-containing media is jumpwise. The average period $\Delta t = t_*$ of formation of the conditions of fracture, i.e., the accumulation of hydrogen and formation of a macrocrack, is equal to the period of repetition of jumps according to which, together with the mean length of jumps $\Delta l = x_*$, we can determine the average macroscopic rate of propagation of the main crack

$$v = \frac{x_*}{t_*}. \quad (2)$$

In [4], the following equation of balance of rates was obtained for the analyzed case on the basis of the energy approach:

$$\frac{\partial l}{\partial t} = \frac{B\sigma_0}{\gamma_0 - \gamma_p} \int_0^{l_p} \frac{\partial C_H(x, t)}{\partial t} \Big|_{t=t_*} dx, \quad (3)$$

where l_p is the length of the plastic zone in the vicinity of the crack tip, γ_p is the specific energy of plastic strains under static loading, $\gamma_p = \sigma_0 \delta$, δ is the crack-tip opening displacement under loading, and σ_0 are the mean normal stresses formed in the process zone according to the well-known δ_c -model of quasibrittle fracture of cracked bodies [2].

We represent the specific fracture energy in the form $\gamma_0 = \sigma_0 \delta_c$, where δ_c is the critical crack-tip opening displacement.

As a result, we obtain the following equation for the crack growth rate in hydrogen-containing media:

$$\frac{\partial l}{\partial t} = \frac{B}{\delta_c - \delta} \int_0^{l_p} \frac{\partial C_H(x, t)}{\partial t} \Big|_{t=t_*} dx. \quad (4)$$

According to [2], we find the concentration of hydrogen in the process zone by the formula

$$C(x, t) = \frac{2C_S \sqrt{\tau} \exp[2m\xi - (4\tau)^{-1}\xi^2]}{\xi\sqrt{\pi} \exp m\xi + 2\sqrt{\tau} \exp(-0.25\xi^2\tau^{-1})}, \quad (5)$$

where $\xi = x(2\delta)^{-1}$, $\tau = Dt/(2\delta)^2$, $m = 0.9\sigma_Y V_H/RT$, D is the diffusion coefficient of hydrogen in the metal, V_H is the partial molar volume of hydrogen in the metal, and R is the universal gas constant.

Further, it is necessary determine the average length x_* of jumps of the crack. In [5], it is shown that the deformation characteristics are especially sensitive to the influence of hydrogen. In some cases, the deformation parameters sharply decrease as the concentration of hydrogen in the metal increases. This is why we use the deformation criterion of strength to establish the conditions of local fracture. Assume that the increment of crack length for time t_* is equal to x_* provided that the following equality is true at the point $x = x_*$ under a given load:

$$\varepsilon_H(x_*, p) = \varepsilon_c(p) - BC(x_*, t_*), \quad (6)$$

where $\varepsilon_c(p)$ is the ultimate level of strain in the material at fracture in the absence of hydrogen.

The levels of strain in the process zone in the hydrogenated and nonhydrogenated materials are determined via the crack-tip opening displacement δ , i.e., we assume that [6]

$$\varepsilon_H(x_*, p) = \frac{\delta}{h}, \quad \varepsilon_c(p) = \frac{\delta_c}{h}, \quad (7)$$

where h is a proportionality factor.

Thus, in view of (2) and (5)–(7), we get the following condition for the determination of x_* :

$$1 - \delta/\delta_c = \alpha C(x_*, x_*/v), \quad (8)$$

where $\alpha = Bh/\delta_c$.

After certain mathematical transformations, relations (5) and (8) yield the following formula for the length of an elementary jump of the crack:

$$x_* \approx \frac{8\alpha C_S D \delta_c \lambda (1 - \lambda) + 4D\alpha^2 C_S^2 \delta_c \lambda + 4D\delta_c \lambda (1 - \lambda)^2}{8\alpha^2 C_S^2 Dm + 8\alpha C_S Dm(1 - \lambda) + \delta_c \lambda \pi v (1 - \lambda)^2}, \quad \lambda = \frac{\delta}{\delta_c}. \quad (9)$$

Further, in view of relations (2), (4), (5), and (9), we arrive at the following equation for the crack growth rate:

$$v = \frac{8B\alpha C_S^2 Dm \delta_c \lambda (\alpha C_S + (1 - \lambda)) \left(\exp\left(\frac{ml_p}{\delta_c \lambda}\right) - 1 \right) - 8D\delta_c \lambda m (1 - \lambda) (2\alpha C_S (1 - \lambda) + (1 - \lambda)^2 + \alpha^2 C_S^2)}{32\alpha C_S m^2 a \delta_c \lambda (1 - \lambda) (\alpha C_S + (1 - \lambda)) - BC_S \delta_c^2 \lambda^2 \pi (1 - \lambda)^2 \left(\exp\left(\frac{ml_p}{\delta_c \lambda}\right) - 1 \right)}. \quad (10)$$

To find the residual service life of the structural element, Eqs. (1) and (10) are supplemented with the following initial and final conditions:

$$t = 0, \quad l(0) = l_0, \quad (11)$$

$$t = t_*, \quad l(t_*) = l_*, \quad (12)$$

where the critical length $l = l_*$ is found from the condition $K_I(l_*) = K_{Ic}$.

Thus, if the characteristics of the material δ_c , α , B , D , C_S , and m are known, then the period of subcritical crack growth in hydrogen-containing media can be found by using relations (1) and (10)–(12).

Evaluation of the Residual Service Life of Elements of a Hydrogen-Fueled Engine in Hydrogen-Containing Media. Consider a cylindrical part of a hydrogen-fueled engine containing hydrogen under certain pressure. The interaction of this structure with neighboring units is equivalent to the application of a bending moment M together with an axial force P and a transverse force S at the edges (Fig. 1). Clearly, the most unfavorable region of location of the stress concentrator (circular groove) is, at the same time, the most hydrogen-dangerous zone. The operating conditions are as follows: $T = 350$ K and $P_{H_2} = 30$ MPa. The structure is made of high-strength steel whose diagram of static crack resistance is known (Fig. 2).

The mechanical characteristics of steel are constant for the indicated operating temperature in the absence of hydrogen: $E = 186.4$ GPa, $\sigma_Y = 953$ MPa, $\sigma_u = 993$ MPa, $\psi = 0.66$, and $K_{Ic} = 130$ MPa $\sqrt{m}$.

The strength analysis with regard for the influence of hydrogen on the material is performed after determination of the SSS in the element. This state is regarded as known and shows that the cracks formed in the minimum section (plane $y = 0$ in Fig. 1) are especially dangerous.

For these cracks, on the basis of the finite-element solution of the problem of SSS of the body with regard for the pressure of hydrogen penetrating in the cracks, the SIF can be found by using the following approximate formula [7]:

$$K_I = \sqrt{\pi l} (A_0 + A_1 l + A_2 l^2) \quad (0 \leq l \leq 7 \text{ mm}), \quad (13)$$

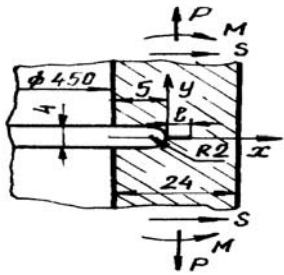


Fig. 1

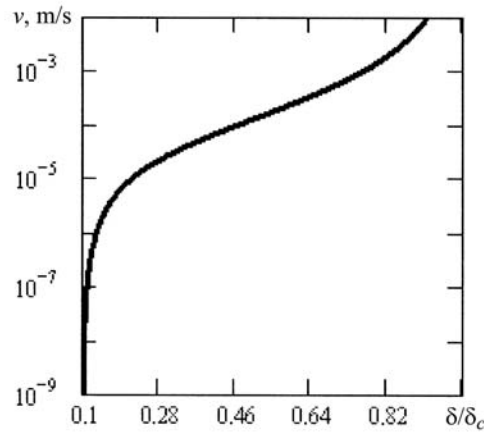


Fig. 2

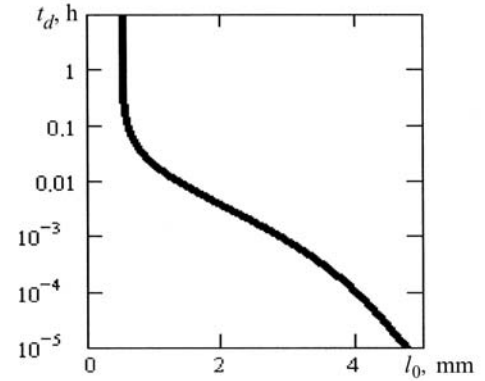


Fig. 3

Fig. 1. Fragment of a working cylinder of a hydrogen-fueled engine.

Fig. 2. Dependence of the crack-growth rate on the crack opening displacement.

Fig. 3. Diagram of the service life of a cylindrical part of a hydrogen-fueled engine.

where l is the crack depth measured from the bottom of the concentrator, $A_0 = 986$ MPa, $A_1 = -136$ MPa/m, and $A_2 = 59.3$ MPa/m².

These parameters can serve as input data for the strength analysis of the material in hydrogen-containing media. Further, by using relation (10), we find the design-basis diagram of static crack resistance of steel under the operating conditions, where $\delta_c = 5.409 \cdot 10^{-5}$ m, $D = 9 \cdot 10^{-10}$ m²/s, $m = 0.5969$, $BC_S = 13.099$, $\alpha C_S = 0.3845$, and $K_{Ith}^{(H)} = 40$ MPa $\sqrt{m}$.

After this, Eq. (1) is solved by the Runge-Kutta method with regard for relation (10) with the indicated initial $[t = 0, l = l_0 (K_I(l_0) = K_{Ith}^{(H)})]$ and final $[t = t_d, l = l_c (K_I(l_c) = K_{Ic})]$ conditions.

As a result of the performed numerical analysis, we can make the following conclusion: Although the investigated element loses its load-bearing capacity in the presence of cracks whose depth is greater than $l_c(K_{Ic}) = 5.7$ mm, only the cracks whose depth is less than 0.64 mm do not propagate under the influence of hydrogen for the indicated operating parameters (Fig. 3). Thus, the structure quite strong under standard conditions can become inoperative under the influence of hydrogen.

Evaluation of the Residual Service Life of a Petroleum-Hydrocracking Reactor. The same procedure can be used for the investigation of serviceability and evaluation of the service life of a petroleum-hydrocracking reactor. The body of the reactor is made of 2.25Cr–1Mo ferritic steel with a thickness of 0.19 m and the following chemical composition (wt.%): 0.14 C, 0.50 Mn, 0.007 P, 0.006 S, 0.04 Si, 2.43 Cr, 1.01 Mo, 0.16 Ni, and 0.06 Cu. The body has a protective hard facing of austenitic stainless steel with a thickness 0.008 m. After long-term operation under conditions of high-temperature hydrogenation of the reactor at a pressure of the medium inside the reactor of 16 MPa and a temperature of 723 K, the process is terminated, i.e., the level of pressure decreases and the medium is cooled down to room temperature.

It is shown that the transient thermal modes characterized by the formation and development of hidden hydrogen-induced defects in the walls of the reactor body can be especially dangerous (Fig. 4) [8]. For these defects, we have $K_I = 2P\sqrt{l/\pi}$. They appear as a result of the supersaturation of the metal with hydrogen under the action of nonstationary and nonuniform temperature fields responsible for the inhomogeneous variations of the solubility of hydrogen in the metal and the formation of overequilibrium pressures in internal defects (Fig. 5).

The degree of the indicated supersaturation and the level of internal pressure depend on the rates of thermal processes, the characteristics of absorption of hydrogen by the metals, and the sizes of the regions with different

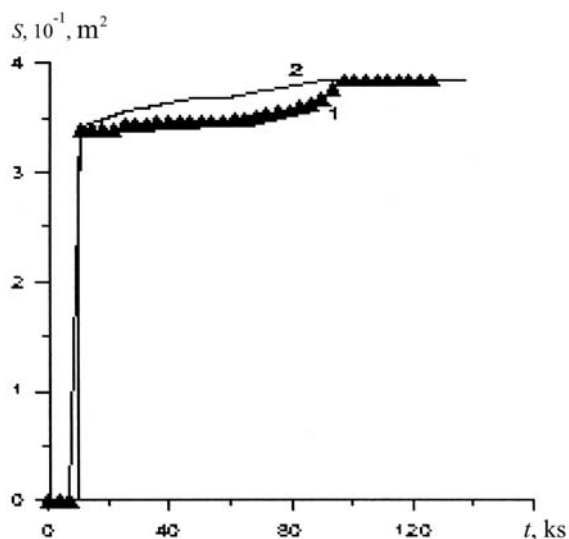


Fig. 4

Fig. 4. Time dependences of the area of an internal crack in a bimetallic wall of the reactor body: (1) experiment, (2) calculation.

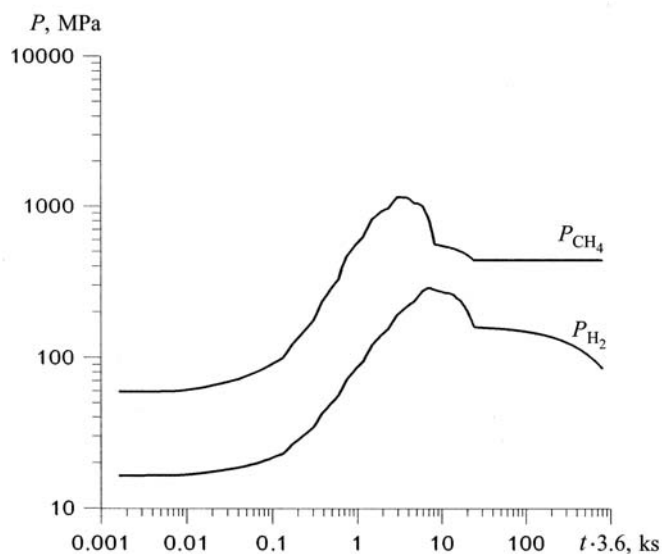


Fig. 5

Fig. 5. Time dependences of the pressure of gases in internal defects obtained as a result of numerical calculations.

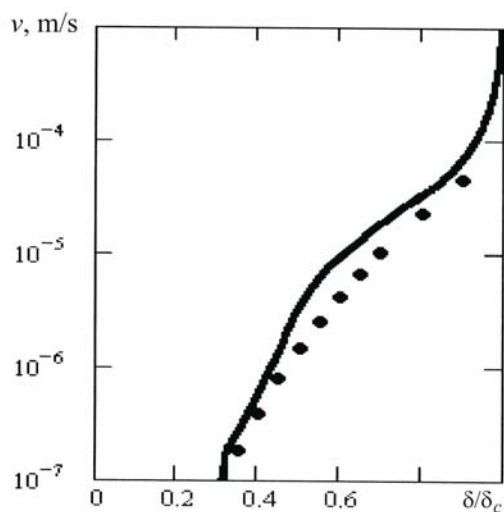


Fig. 6

Fig. 6. Diagram of static crack resistance of 2.25Cr-1Mo steel: the solid line corresponds to the theoretical data obtained by using relation (10) and the dark symbols correspond to the experimental data [9].

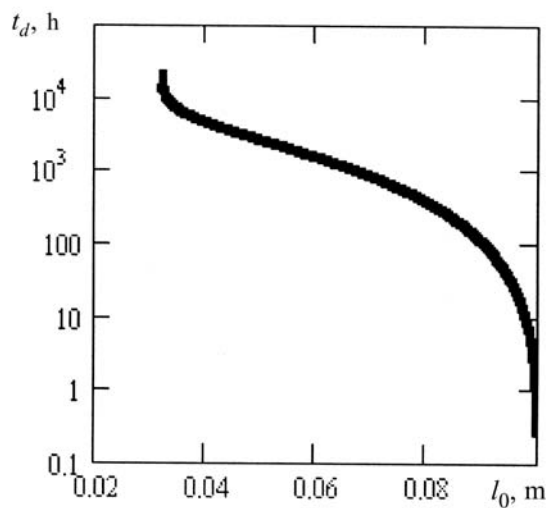


Fig. 7

Fig. 7. Diagram of the service life of an element of petroleum-hydrocracking reactor.

solubilities of hydrogen. All these factors should be taken into account both in the design, strength analysis, and evaluation of the service life of the reactors and in the determination of the admissible modes of operation.

In [9], the diagram of static crack resistance of 2.25Cr-1Mo steel is experimentally constructed for the following operating conditions: $T = 450^\circ\text{C}$ and $P_{\text{H}_2} = 16 \text{ MPa}$ (Fig. 6). By using relation (10), we determine the dependence of the crack-growth rate on the crack opening displacement (Fig. 6), where $\delta_c = 2.069 \cdot 10^{-4} \text{ m}$,

$D = 2 \cdot 10^{-9} \text{ m}^2/\text{s}$, $m = 0.2335$, $\sigma_Y = 426 \text{ MPa}$, $K_{Ic} = 170 \text{ MPa}\sqrt{\text{m}}$, $BC_S = 1.5197$, and $\alpha C_S = 4.1667$. As in the previous case, Eq. (1) is solved by the Runge-Kutta method with regard for Eq. (10) with the corresponding initial $[t = 0, l = l_0 (K_I(l_0) = K_{Ith}^{(H)})]$ and final $[t = t_d, l = l_c (K_I(l_c) = K_{Ic})]$ conditions. As a result, we obtain the dependence of the time of subcritical crack growth on the initial size of the crack (Fig. 7).

Thus, the proposed computational model enables one to determine the kinetics of crack growth in hydrogen, the residual service life of structural elements operating in hydrogen, and the admissible sizes of detected defects from the viewpoint of their hydrogen-induced fracture and specified service life.

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REFERENCES

1. A. E. Andreikiv, *Three-Dimensional Problems of the Theory of Cracks* [in Russian], Naukova Dumka, Kiev (1982).
2. V. V. Panasyuk, *Mechanics of Quasibrittle Fracture of Materials* [in Russian], Naukova Dumka, Kiev (1991).
3. M. P. Savruk, *Fracture Mechanics and Strength of Materials. Handbook* [in Russian], Vol. 2, Naukova Dumka, Kiev (1988).
4. O. Gembara, "Computational model of hydrogen-assisted crack growth in metals," in: V. V. Panasyuk (Ed.), *Fracture Mechanics and Strength of Structures* [in Ukrainian], Karpenko Physicomechanical Institute, National Academy of Sciences of Ukraine, Lvov (2004), pp. 551–556.
5. R. M. N. McMeeking, "Finite deformation analysis of crack tip opening in elastic-plastic materials and implication for fracture," *J. Mech. Phys. Solids*, **25**, No. 5, 357–381 (1977).
6. A. E. Andreikiv, Ya. L. Ivanitskii, Z. O. Terletskaia, and M. B. Kit, "Evaluation of the service life of a pipe of oil pipeline containing a surface crack under biaxial block loading," *Fiz.-Khim. Mekh. Mater.*, No. 3, 103–108 (2004).
7. A. E. Andreikiv, V. V. Panasyuk, L. I. Polyakov, and V. S. Kharin, *Mechanics of Hydrogen Embrittlement of Metals and Strength Analysis of Structural Elements* [in Russian], Preprint No. 133, Karpenko Physicomechanical Institute, National Academy of Sciences of Ukraine, Lvov (1987).
8. A. E. Andreikiv and O. V. Gembara, "Evaluation of the service life of elements of petroleum-hydrocracking reactors," *Mashynoznavstvo*, No. 4-5, 5–8 (1998).
9. T. Iwadata, T. Nomura, and J. Watanabe, "Hydrogen effect on remaining life of hydroprocessing reactors," *Corrosion*, No. 2, 103–112 (1998).