PREDICTION OF THE RESIDUAL DURABILITY OF STRUCTURAL ELEMENTS UNDER THE DUAL INFLUENCE OF HYDROGEN

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On the basis of the previously developed calculation model of hydrogen-induced crack growth in metals under the action of long-term static loading under various HELP, HEDE mechanisms, kinetic diagrams of hydrogen cracking of steels were constructed 4340 and 4147 under different hydrogenation regimes. The residual durability of the plate with a crack under dual hydrogen exposure was calculated.

Keywords: hydrogen diffusion, hydrogen concentration, hydrogen-containing environment, local plastic deformation, mathematical model, crack propagation, residual durability

Introduction. Research over the past 20 years has shown [1] that for steels, depending on the concentration of hydrogen in the metal, two main mechanisms of hydrogen influence can simultaneously operate, namely: HEDE - hydrogen-enhanced decohesion and HELP - hydrogen enhanced localized plasticity. It was established that the transition between the mechanisms of hydrogen degradation depends on the concentration of hydrogen and the conditions of the applied stresses. The coexistence of different mechanisms of hydrogen influence of deformation and their simultaneous action in steels is still not sufficiently investigated, while establishing the dominant mechanism is an extremely difficult and urgent problem. In the work, an attempt was made to establish the influence of the hydrogenation mechanism on the residual durability.

Prediction of residual life of a plate with crack. The residual durability of structural elements operated under the influence of hydrogen-containing environments is mainly determined by the duration of pre-critical crack growth and is estimated based on the solution of the equation [2]

$$\frac{dl}{dt} = v(K_{\mathrm{I}} ,C) \qquad (1)$$

under initial and final conditions:

$$l\left(t = 0\right) = l_0 \;; \qquad l\left(t_*\right) = l_c \,,$$

where l is the crack length; K_I – stress intensity factor; C – hydrogen concentration; the crack growth rate function $v(K_I, C)$ is obtained within the framework of the corresponding calculation models.

To evaluate the effect of the hydrogenation mechanism on the residual durability, a plate with a straight crack under a tensile load P, which is applied perpendicular to the crack line, was considered. We considered two regimes of hydrogen diffusion into the prefracture zone.

For their implementation in the calculations, it was assumed that the plates are finitely hydrogenation to the same concentration of C_0, but the time to reach such a concentration in the zone of prefracture near the top of the crack is different. In the first mode (I) (Fig. 1a), the plate is previously unhydrogenation. Diffusion of hydrogen occurs only through the top of the crack, and additional time is required to flood the prefracture zone. Therefore, the concentration there is initially insignificant and we observe plasticization, which with increasing time turns into brittleness, that is, the compatible mechanism HELP→HEDE will be implemented. In the diffusion problem, this is modeled by boundary conditions

$$C(0,t) = C_S, \; C(x,0) = 0 \qquad (2)$$

The second mode (II) (Fig. 1b), in which the HEDE mechanism is implemented. The plate is pre-hydrogenated to a certain level of C_0 concentration. Hydrogen redistribution has already taken place and the prefracture zone is also hydrogenated. In the diffusion problem, this is modeled by boundary conditions

$$C(x,0) = C_0 \qquad (3)$$

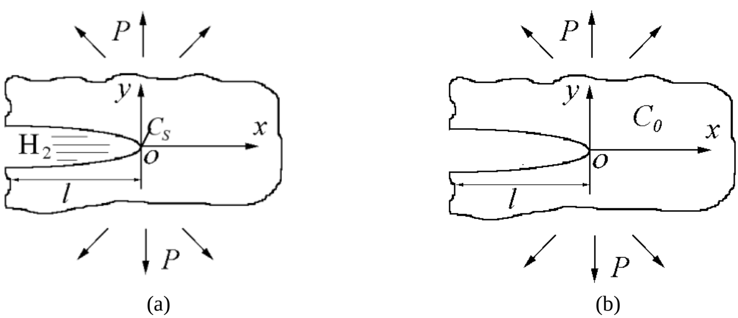
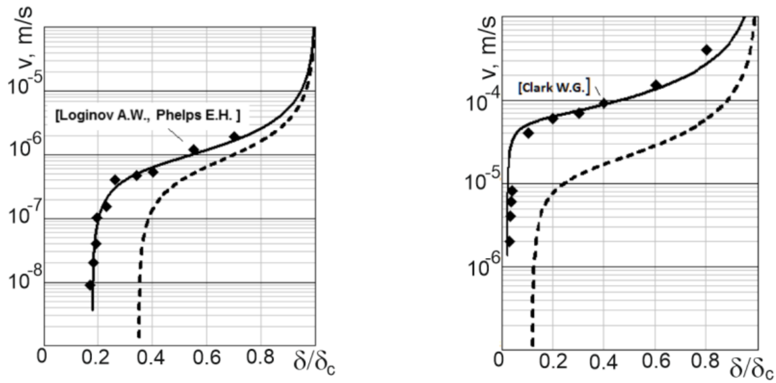


Fig 1. Scheme of a loaded body with a crack under different conditions of hydrogenation: (a) I mode; (b) II mode.

Using previously developed calculation models [3] and experimental data [4,5], kinetic diagrams of crack growth were constructed. In Fig. 2 shows the dependences of the crack growth rate on its opening, calculated (curves), for two hydrogenation modes and experimental data (symbols) [4, 5] for steels 4147 (Fig. 2 a) and 4340 (Fig. 2 b). During calculations for steel 4147, the following characteristics were used: $\delta_c = 0{,}89 \cdot 10^{-5}$ m, $D = 10^{-11}\, m^2/s$, $m = 0{,}6528$, $\sigma_T = 869 MPa$, $K_{Ic} = 160 MPa\sqrt{m}$; для сталі 4340 – $\delta_c = 5{,}833 \cdot 10^{-5}$ m, $D = 10^{-10}\, m^2/s$, $\sigma_T = 1240 MPa$, $K_{Ic} = 154 MPa\sqrt{m}$, $m = 0{,}9061$, $BC_S = 1{,}9$, $\alpha C_S = 1{,}847$.

Analysis of the data in Fig. 2 shows that the calculated curve of subcritical growth of a crack in a metal subjected to tension under the II hydrogenation mode is in satisfactory agreement with experimental data and can be used to predict the residual durability of structural elements under such conditions.

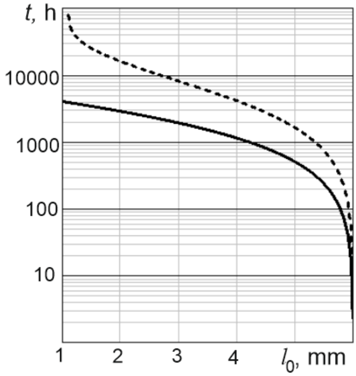


(a) (b)

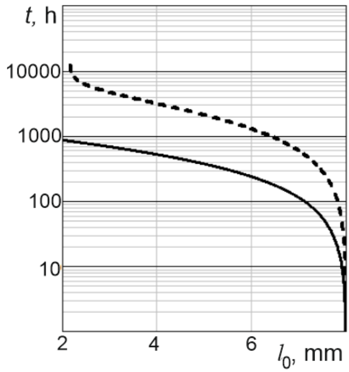
Fig. 2. The dependence of the crack growth rate on its opening for steels 4147 (a) and 4340 (b) (curves – calculation; circles – experimental data [4, 5]): dashed curve – I hydrogenation mode; the solid curve is the II hydrogenation mode.

In Fig. 3. calculated results of the time to failure depending on the initial size of the crack are given.

We can see that thanks to the gradual hydrogenation through the top of the crack, i.e. when a small concentration of hydrogen accumulates in the prefracture zone, the implementation of the HELP mechanism is first observed, i.e. plasticization occurs near the top of the crack, the crack becomes blunt and does not spread until a sufficient amount of hydrogen accumulates. In mode I, the crack begins to grow with a larger opening and at a lower speed, compared to mode II hydrogenation, when the plate is already sufficiently hydrogenated to implement hydrogen embrittlement through the HEDE mechanism. Accordingly, the residual durability of the plate in the I mode is an order of magnitude greater than in the II mode. This is observed for both steels.



(a)



(b)

Fig. 3. The dependence of the residual durability of the model plate on the initial crack size for steels 4147 (a) and 4340 (b): dashed curve – I hydrogenation mode; the solid curve is the II hydrogenation mode.

Conclusions. It has been quantitatively established that for the values of the concentration of pre-absorbed hydrogen, the durability of a plate with a crack is an order of magnitude lower than for the concentration of hydrogen that gradually diffuses from the top of the crack into the prefracture zone. This is due to the fact that the gradual hydrogenation of the prefracture zone initially plasticizes it, thereby blunting the top of the crack, increasing its opening and inhibiting its propagation.

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