

# STATIC CRACK RESISTANCE OF HYDROGENATED HIGH-STRENGTH STEELS

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## ABSTRACT

The mathematical model of retarded fracture for the hydrogenated high-strength steels was built. The conceptions of fracture mechanics for the low-scale flow were used during the analysis of the critical stress intensity factor under long-term static loading ( $K_{IHC}$ ). When calculating the crack propagation rate  $U$  at  $K > K_{IHC}$  hydrogen diffusion into the zone of prefracture is described in accordance with the diffusion equation solution for the saturation process of thin platelet with impurities at feeding linear flow in the semi-infinite medium. The diagrammatic interpretation of the obtained relationships between  $K_{IHC}$  and  $U$  and test conditions, and also between diffusion-mobile hydrogen content and material parameters is given in this paper.

## KEYWORDS

High-strength steels. fracture, crack resistance, hydrogen, model.

High-strength steels crack resistance  $K_{IHC}$  and crack propagation rate  $U$  under long-term static loading with the account of hydrogen embrittlement and cold brittleness are considered in the present paper. The conceptions of A.Kfourri and J.Rice (1979) for elastoplastic body fracture process were used in the suggested model. In this paper the relationship was derived for contour integral  $J$  at low-scale flow

$$J = 0.7 * \xi * \exp(0.43/\xi) * G, \quad (1)$$

$$\text{where } \xi = [S_{0.2} * \Delta a * (1 - \sqrt{\nu})] / (E * G^\Delta), \quad (2)$$

$G^\Delta$  - strain energy release rate at the crack tip on its propagation by the step  $\Delta a$ .

$\nu$ , E and  $S_{0.2}$  - Poisson's ratio, elasticity modulus and yield strength at uniaxial tension, respectively.

As applied to hydrogenated metal fracture, it is anticipated that the fracture step is determined only by the material structure state, and  $G^A$  value is linearly decreased with hydrogen concentration increase C.

$$G^A = G_0^A - \beta C, \quad (3)$$

where  $G_0^A$  and  $\beta$  - constants for the given structure state. After simple transformations of 1-3 relationships and when passing from J contour integral to stress intensity factor value K we obtain

$$\ln(K_{IC} / K) = MC \cdot \nu^2 \quad (4)$$

$$\text{where } M = 0,25 * E * \beta / [(1 - \nu^2) * \Delta a * S_{0.2}^2] \quad (5)$$

but for  $K_{IC}$  value the following relationship is accepted

$$K_{IC} = 0,84 * S_{0.2} * \sqrt{\Delta a} * \exp\{[0,215 * G_0^A] / [\Delta a * S_{0.2}^2 * (1 - \nu^2)]\} \quad (6)$$

The incubation period to the first crack jump, crack propagation period and the final fracture when achieving  $K_{IC}$  value are inherent within the limits of the considered model for the fracture process of the uniformly hydrogenated and long-term loaded cracked sample. Crack jumps occur in the elastoplastic zone of the crack tip - the prefracture zone (PFZ). The elastoplastic state of PFZ results in hydrogen solubility S increase in it by  $\alpha$  times compared to its average concentration  $C_0$ .

$$S = \alpha * C_0 \quad (7)$$

Hydrogen diffusion in PFZ ensures the achievement of the critical hydrogen concentration  $C_c$  which causes crack jump by  $\Delta a$  value at the acting K value.  $C_c$  value  $\leq S$ , i. e.

$$C_c = \eta * S, \quad \eta \leq 1 \quad (8)$$

The equilibrium hydrogen concentration ( $\eta = 1$ ) is achieved at long enough loading time in PFZ. In the case of  $K = K_{IHC}$  we obtain from the relationship 4:

$$\ln(K_{IC} / K_{IHC}) = MS = M \alpha C_0 \quad (9)$$

The relationship 9 defines the dependence of  $K_{IHC}$  value on material structure state, standard mechanical properties level, test temperature T and diffusion-mobile hydrogen content in the metal.

In order to carry out the numerical calculations the following relationship well approximating the temperature dependences of  $K_{IC}$  and  $S_{0.2}$  values are introduced:

$$K_{IC} = K_{IC}^L + (K_{IC}^{UP} - K_{IC}^L) (1 - \exp[-3 * (T / T_{CB}^{UP})^n]) \quad (10)$$

$$S_{0.2} = A_1 + [A_2 / (T + A_3)] \quad (11)$$

$$n = 4 / \ln(T_{CB}^L / T_{CB}^{UP}), \text{ where} \quad (12)$$

$K_{IC}^L$  and  $K_{IC}^{UP}$  - crack resistance, respectively, at the temperatures of cold brittleness lower ( $T_{CB}^L$ ) and upper ( $T_{CB}^{UP}$ ) thresholds;  $A_1$ ,  $A_2$  and  $A_3$  - coefficients, obtained from the experimental results. Besides, elasticity properties E and  $\nu$  have weak temperature dependence at not very high temperatures, which in accordance with the expression 5 gives the relationship:

$$M(T) \sim 1 / S_{0.2}^2(T) \quad (13)$$

$\alpha$  value is calculated according to the well-known (P.U.Geld et al., 1979; C.McMahon, et al., 1979) relationship:

$$\alpha = \exp(\bar{\sigma}_0 * \bar{V}_H / RT) \quad (14)$$

where  $\bar{V}_H$  - partial specific hydrogen volume in steel,  $\bar{\sigma}_0$  - hydrostatic stresses in PFZ.

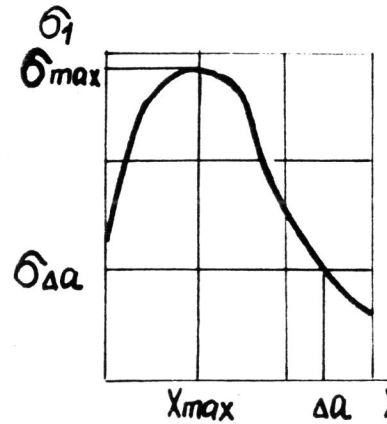
Having substituted the known meanings of R and  $\bar{V}_H$  values (P.U.Geld et al., 1979) in the relationship 14

( $R = 8,32 \text{ j/mol*deg}$  and  $\bar{V}_H = 2 \text{ cm}^3 / \text{mol}$ ) we obtain

$$\alpha = \exp\{[(2,36 * \bar{\sigma}_0) / T]\} \quad (15)$$

In accordance with the conceptions of fracture mechanics the distribution of the highest principal stresses  $\sigma_1$  in the crack tip at plain strain is given in Fig 1. Taking into account, that when calculating  $\bar{\sigma}_0$  value is of estimation character

in 15 formula  $\bar{\sigma}_0$  is accepted as equal to the  $\sigma_0$  maximum stresses level  $\sigma_{max}$  at  $\Delta a \leq X_{max}$  or to the level of the highest principal stresses  $\sigma_{\Delta a}$  at  $\Delta a > X_{max}$ . For the relationship downgoing branch of  $\sigma_1 = f(X)$  the relationship



$$\sigma_1 \approx \sigma_{max} * \sqrt{X_{max} / X} \quad (16)$$

is true, from which it can be obtained:

$$\bar{\sigma}_0 \approx \sigma_{\Delta a} = \sigma_{max} * (K / K_{\Delta}) \quad (17)$$

$$\text{where } K_{\Delta} = \sqrt{\Delta a * S_{0.2} * E} \quad (18)$$

The relationship 17 is true for small  $K < K_{\Delta}$ , when  $X_{max} = K^2 / (S_{0.2} * E) < \Delta a$

$$\text{At } K > K_{\Delta} \quad \bar{\sigma}_0 \approx \sigma_{max} \quad (19)$$

The introduction of generalized relationship is expedient for the whole range of K instead of the relationships 17 and 19. We suggest the generalized expression for  $\alpha$  in the form of

$$\alpha = \exp\{[(B/T) * S_{0.2} * (1 - \exp[-2 * (K / K_{\Delta})^{1/4}])]\} \quad (20)$$

Fig.1 The distribution of the highest principal stresses  $\sigma_1$  in the crack tip at plain strain.

where B - is defined from the relationship:

$$\sigma_{max} = (B / 2.36) * S_{0.2} \quad (21)$$

When calculating  $K_{IHC}$  meanings in the expression 20, K value is substituted for  $K_{IHC}$ .

In the considered model the numerical calculations of the temperature and the concentration dependence of K value are carried out for UNS-2 (08X15N5A2T) steel, containing diffusion-mobile hydrogen of metallurgical origin. The heat treatment of the steel was performed as follows: quenching from 1273 K and temper at 698 K for the strength of  $\sigma_B = 1350$  MPa. Determination of the standard mechanical characteristics and  $K_{Ic}$  values at different temperatures allows to obtain the following parameter values:

$$A_1 = 40; A_2 = 50000; A_3 = 370; K_{Ic}^{up} = 176 \text{ MPa} * \text{m}^{1/2}$$

$$K_{Ic}^L = 38.4 \text{ MPa} * \text{m}^{1/2}; T_{CB}^{up} = 283 \text{ K}; T_{CB}^L = 203 \text{ K}; n=12,25$$

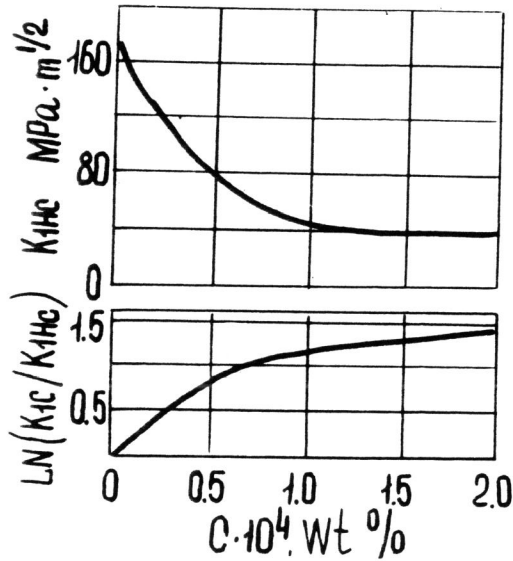


Fig. 2. Experimental dependence of crack resistance on hydrogen concentration.

$$(\ln \Delta)_{max} = \ln(K_{Ic} / K_{IHC}) / C = 1.6 \text{ (at } K_{IHC} > K_{\Delta}) \quad (23)$$

The obtained theoretical dependencies and the presented limited volume of experimental results make it possible to conduct numerical calculations and diagrammatic

The experimental dependence of  $K_{IHC}$  on diffusion-mobile hydrogen concentration in UNS-2 steel (Fig. 2) was obtained at room temperature. The mathematical processing of these results shows (Fig. 2), that the linear dependence of  $\ln(K_{Ic} / K_{IHC})$  value on C concentration is observed at low hydrogen concentrations and high  $K_{IHC}$  values (approximately at  $K_{IHC} > K_{Ic} / 3 \approx 58.6 \text{ MPa} * \text{m}^{1/2}$ ). In accordance with the above-mentioned conceptions one can assume for the case under consideration ( $T = 293 \text{ K}$ ):

$$K_{\Delta} = K_{Ic} / 3 = 58.6 \text{ MPa} * \text{m}^{1/2} \quad (22)$$

interpretations of the mathematical models for  $K_{IHC}$  value. However, preliminarily it is necessary to estimate the numerical values of B. It follows from the continual model for the plain strain, that  $B \approx 6$ , and accounting for the local shear stress at the top of dislocations cluster gives  $B \approx 16$  (C. McMahon et al., 1977). In our calculations we assumed  $B=10$ . Diagrammatic interpretation of the mathematical model under consideration for K value is shown in Fig. 3 and 4.

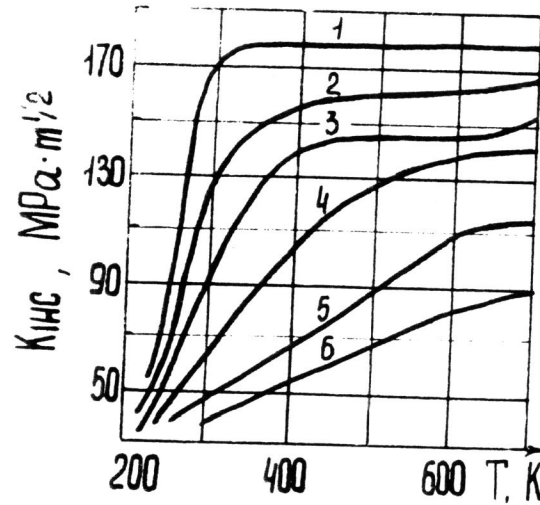


Fig. 3.  $K_{IHC}$  value with the hydrogen content in wt% as the function of temperature.

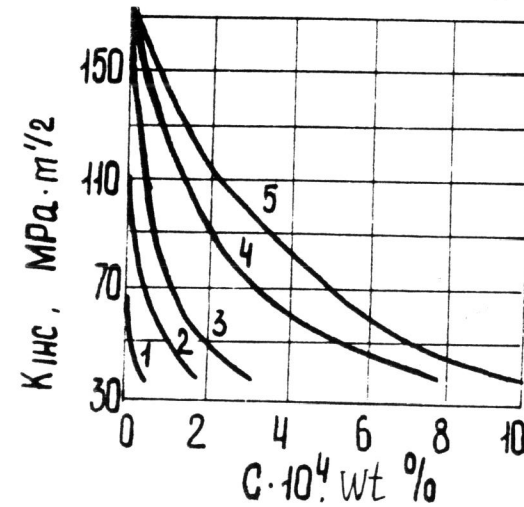


Fig. 4.  $K_{IHC}$  value at the temperatures K as the function of concentration of concentration

The calculation of the hydrogen diffusion process in PFZ is necessary, when analyzing the fracture kinetics at  $K > K_{iHC}$ . We used the problem of the thin plate saturation with the impurities at the feeding linear flow in the semi-infinite medium (McLean D., 1960). In conformity with this solution it can be written for the  $i$  - jump of the crack.

$$(C_c^i - C^i) / (S - C^i) = 1 - \exp(-Z_i^2) \operatorname{erfc}(Z_i), \quad (24)$$

$$\text{where } Z_i = 2\sqrt{D \cdot \tau_i} / (\alpha \cdot h_i) \quad (25)$$

$$h_i = 0,5 \cdot [K_i^2 / (S_{O_2} \cdot E)] \quad (26)$$

$$D = D_0 \exp[-Q / RT] \quad (27)$$

$h$  - PFZ width,  
 $\tau$  - the interval between two jumps,  
 $D$  - coefficient of hydrogen diffusion,  
 $Q$  - energy of hydrogen diffusion activation,  
 index "i" - indicates the current moment of "i" jump.

By adopting the linear relation between  $C_c^i$  and  $C^i$ , i.e.

$$C^i = r C_c^i \quad (r < 1) \text{ and introducing the designation}$$

$$F(Z_i) = 1 - \exp(-Z_i^2) \cdot \operatorname{erfc}(Z_i) \quad (28)$$

$$F(Z_i) = (1 - r) / [M \cdot \alpha \cdot C / \ln(K_{iC} / K_i) - r] \quad (29)$$

The transition to the crack growth rate  $U$  is conducted basing on the ratio  $U = \Delta a / \tau_i$  and the expressions 25 and 27. Simple transformations allow to obtain the relationship

$$\ln(U_i \cdot Y) = 2 \cdot \ln[S_{O_2} / (Z_i \cdot \alpha_i \cdot K_i^2)] - Q / RT, \quad (30)$$

where  $Y = 1 / (16 \cdot D_0 \cdot \Delta a \cdot E^2)$ , and the value  $Z_i$  is defined from the relationship 29.

The selection of  $B$ ,  $r$  and  $Q$  values is necessary for numerical calculations of crack propagation rate, basing on the obtained relationships. As it was mentioned above, the estimation  $B = 10$  was assumed. For the activation energy the value  $Q = 9500$  cal/mol was taken, which is close to the literature data for high-alloyed alloys (P.U.Geld and R.A.Ryabov, 1974). The estimation of  $r$  value gives the magnitude from 0,2 (at  $K$ , close to  $K_{iHC}$ ) to  $r = 1$  (at  $K$ , close to  $K_{iHC}$ ). We have taken the estimation  $r = 0,6$  for numerical calculations. The diagrammatic interpretation of the crack propagation mathematical model for UNS-2 steel is shown in Fig. 5, 6, 7. The experimental verification has confirmed several qualitative deductions of the model, including the shift to the side of the elevated temperatures of the functional

relationship maximum  $\ln(U \cdot Y) = f(T)$  with the growth of the acting stress intensity factor  $K$ .

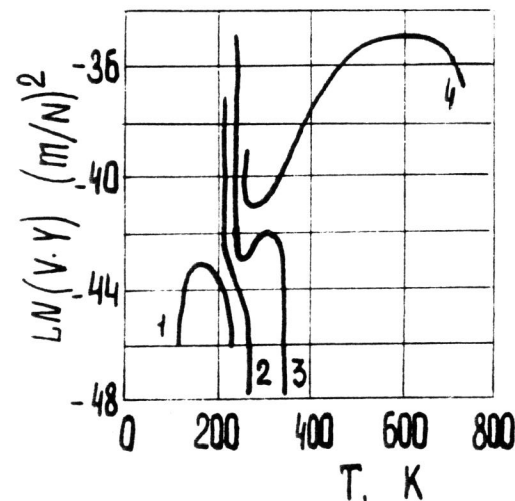


Fig. 5. The relationship  $\ln(U \cdot Y) = f(T)$  at  $C = 10^{-4}$ , wt% and  $K$  value ( $MPa \cdot m^{1/2}$ ):  
 38 (curve 1)  
 51 (curve 2)  
 83 (curve 3)  
 144 (curve 4)

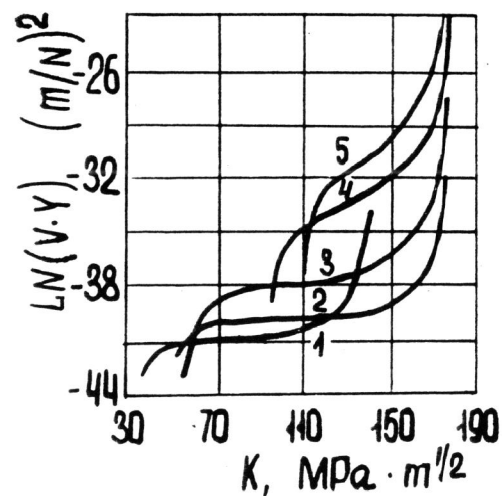


Fig. 6. The relationship  $\ln(U \cdot Y) = f(K)$  at  $C = 2 \cdot 10^{-4}$  wt%, temperatures  $K$ :  
 265 (curve 1)  
 300 (curve 2)  
 350 (curve 3)  
 500 (curve 4)  
 700 (curve 5)

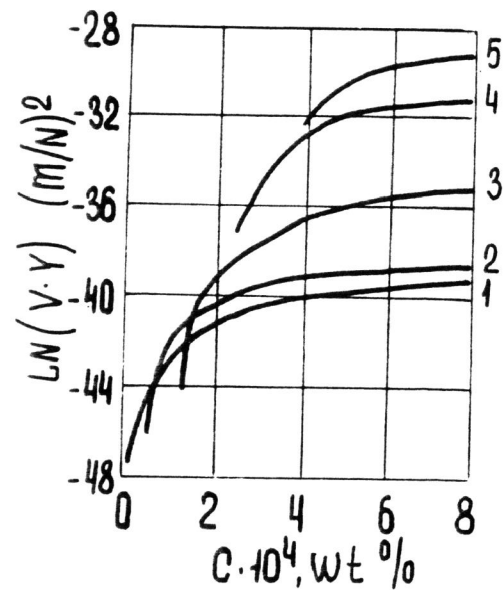


Fig. 7. The relationship  $\ln(U*Y)=f(C)$  at  $K=83 \text{ MPa}\cdot\text{m}^{1/2}$  and temperatures K: 265 (curve 1) 300 (curve 2) 350 (curve 3) 500 (curve 4) 700 (curve 5)

#### CONCLUSION

The mathematical model has been developed for crack resistance characteristics ( $K_{IHC}$  and  $U$ ) under long-term static loading of hydrogenated high-strength steels. The model allows to carry out the numerical calculations for different loading conditions, test temperatures, the content of diffusion-mobile hydrogen and the material characteristics.

#### REFERENCES

- Geld P.v., Ryabov R.A., (1974), Hydrogen in metals and alloys, Metallurgiya, Moscow.
- Geld P.U., Ryabov R.A., Kodes E.S., (1979), Hydrogen and imperfection of metal structure, Metallurgiya, Moscow.
- McLean D., (1960), Grain boundaries in metals, Metallurgiya, Moscow.
- McMahon C., Briant K., Banerjy S., (1979), The effect of hydrogen and impurities on the brittle fracture of steel, col. Fracture mechanics. Metals fracture, (A.U.Ishlinsky, G.G.Cherny), 17, 109-133, Mir, Moscow.
- Kfourri A., Rice J., (1979), The rate of strain energy release with the crack size increase to the final value in the elastic-plastic medium, col. Fracture mechanics, Materials fracture, (A.U.Ishlinsky, G.G.Cherny), 17, 19-39, Mir, Moscow.