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Assessment of hydrogen effect on fracture resistance under complex-mode loading

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ABSTRACT

Deformation and force criteria of the limiting-equilibrium state for a plate with an arbitrarily oriented crack under tension and under the influence of hydrogen-containing environment are proposed. The experimental investigations of the limiting-equilibrium state of lamellar specimens made of 09G2S steel with a central inclined crack in hydrogen environment and also in air under tension with different initial crack inclination angles were performed to check the criteria. Under specimen fracture the forces of the crack start were recorded. Experimental data agree well with calculation dependences.

1. Introduction

In practice a majority of structural elements and machine parts operate in the conditions of complex loading. In such elements the complex stress–strain state arises at structural stress concentrators. To describe the crack propagation process under mixed mode loading new criteria and models [1–6] are proposed, the contribution of each loading mechanism into the stress–strain state in the vicinity of the crack tip for cracks of given dimensions and orientation is numerically and experimentally analyzed [7,8]. In cases when a deformable solid with a crack is subjected to the complex mode loading effect, that is all stress intensity factors (SIF) at the crack tip are not equal to zero ($K_{I\beta} \neq 0, K_{II\beta} \neq 0, K_{III\beta} \neq 0$), the limiting load ($p = p_*$) is evaluated [5] by the criterion equation:

$$\left(\frac{K_{I\beta}}{K_{Ic}}\right)^{n_1} + \left(\frac{K_{II\beta}}{K_{IIc}}\right)^{n_2} + \left(\frac{K_{III\beta}}{K_{IIIc}}\right)^{n_3} = 1, \tag{1}$$

where K_{ic} ($i = I, II, III$) are crack growth resistance characteristics, corresponding to the material fracture mode (Modes I, II, III); n_j ($j = 1, 2, 3$) are structural-sensitive parameters determined from the experiment.

If deformation characteristics of the crack growth resistance δ_{ic} ($i = I, II, III$) are used, Eq. (1) becomes [5]

$$\left(\frac{\delta_{Ip}}{\delta_{Ic}}\right)^{m_1} + \left(\frac{\delta_{IIp}}{\delta_{IIc}}\right)^{m_2} + \left(\frac{\delta_{IIIp}}{\delta_{IIIc}}\right)^{m_3} = 1, \tag{2}$$

where δ_{ip} ($i = I, II, III$) are determined by the load value and are to be calculated; m_j ($j = 1, 2, 3$) are the structural-sensitive parameters determined from the experiment.

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Nomenclature

$K_{I\beta}$, K_{Ic}	stress intensity factor and its critical value under Mode I loading, MPa $\sqrt{m}$
$K_{II\beta}$, K_{IIc}	stress intensity factor and its critical value under Mode II loading, MPa $\sqrt{m}$
$K_{III\beta}$, K_{IIIc}	stress intensity factor and its critical value under Mode III loading, MPa $\sqrt{m}$
δ_{Ip}, δ_{Ic}	crack tip opening displacement and its critical value under Mode I loading without hydrogen, mm
$\delta_{IIp}, \delta_{IIc}$	crack tip opening displacement and its critical value under Mode II loading without hydrogen, mm
$\delta_{IIIp}, \delta_{IIIc}$	crack tip opening displacement and its critical value under Mode III loading without hydrogen, mm
$\delta_{Ic}^{(H)}, \delta_{IIc}^{(H)}, \delta_{IIIc}^{(H)}$	critical crack tip opening displacement with hydrogen, mm
δ_{i*}	critical crack tip opening displacement under complex-mode loading without hydrogen, mm
$\delta_{i*}^{(H)}$	critical crack tip opening displacement under complex-mode loading with hydrogen, mm
p_*	limiting loading, MPa
C_H	hydrogen concentration, ppm
σ_y	yield stress, MPa
σ_u	ultimate stress, MPa
δ	elongation, %
ψ	reduction in area, %
ε_c	critical value of tensile deformation without hydrogen
$\varepsilon_c^{(H)}$	critical value of tensile deformation with hydrogen
C_s	hydrogen concentration on the metal surface at the crack tip, ppm
C_0	initial concentration of hydrogen, ppm
α	an inclination angle of the stress concentrator
β	an angle of the initial direction of the crack propagation
P	hydrogen pressure, Pa
T	temperature, K
V_H	partial molar hydrogen volume
R	universal gas constant
D	coefficient of hydrogen diffusion, m^2/s

For practical application of these criteria the material crack growth resistance characteristics K_{Ic}, K_{IIc}, K_{IIIc} or δ_{Ic}, δ_{IIc}, δ_{IIIc}, as well as n_j, m_j (j = 1, 2, 3) parameters should be evaluated from the experiment. In addition the values of $K_{I\beta}$, $K_{II\beta}$, $K_{III\beta}$, δ_{Ip}, δ_{IIp}, δ_{IIIp} should be determined, depending on the conditions of structural element loading, where β is an angle of the initial direction of crack propagation (Fig. 1).

Papers [6,10–12] present special theoretical–experimental researches into the limiting equilibrium states for several materials in the case of complex mode loading and hydrogen influence, namely: normal tear (I)–transversal shear (II), and also normal tear (I)–longitudinal shear (III). It is shown, that criterion (1) for $n_j = 4$, and criterion (2) for $m_j = 2$ agree well with experimental values.

The environment, where the material deformation and fracture occur, has a significant influence on its physicomechanical characteristics, namely the strength and crack growth resistance, and it also changes the conditions of the elasto-plastic deformation and occurrence of the limiting equilibrium state [10–16]. A quantitative evaluation of the hydrogen concentration in the process zone is one of the most important items of the analysis of crack initiation and propagation in metals in the hydrogen presence. This is connected with the fact that hydrogen diffusion into the metal is a step that regulates the preparation of the fracture event at the crack contour with further crack propagation. In a deformed body at the structural stress concentrators where the complex stress–strain state of the material is formed, the effect of hydrogen environment has been studied insufficiently. Therefore the aim of this paper is to develop the methods and determine the characteristics of the material fracture resistance in hydrogen under the complex stress–strain state and also to formulate the criterion of the limiting equilibrium state of cracked bodies under hydrogen effect.

2. Experimental procedure and results

Experimental investigations were performed on 09G2S sheet steel specimens. Mechanical characteristics of 09G2S steel were determined in laboratory conditions under tension of the lamellar specimens of a width of 20 mm and a thickness of 1.5 mm. The rate of the active grip motion in all cases was 0.5 mm/min. Chemical composition and mechanical characteristics of 09G2S steel are presented in Tables 1 and 2.

Experimental investigations under the complex stress–strain state were carried out under the lamellar specimens tension (Fig. 1a) of a width of $2b$ = 120 mm. In plane specimens the notches of a length of $2L_0$ = 20 mm with different orientation angles α with respect to the axis OX were created with a special disk cutter (diameter – 40 mm, thickness – 0.2 mm) sharpened at an angle of 60° with a radius at the tip $\rho \leqslant 0.1$ mm.