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Empirically-specified environmental assisted cracking model

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Abstract

Based on various mechanisms of hydrogen diffusion in metals, different crack propagation models have been developed. Here, empirically specified model of crack propagation in structure components, which are simultaneously subjected to aggressive hydrogen environment influence and cycling, is presented. The model uses two different approaches to problem solving, i.e. the influence of aggressive hydrogen environment on material and the fatigue. A developed environmental assisted cracking model assumes that either the influence of aggressive hydrogen environment or the fatigue initiates a local fracture of structure component. This model enables estimating a structure component life.

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Keywords: Hydrogen cracking; Growth; Fatigue; Life

1. Introduction

Hydrogen embrittlement is a form of environmentally assisted failure under the action of hydrogen often in combination with stress resulting in reduced of the load bearing capacity of a component. Hydrogen embrittlement in metal alloys occurs in a diversity of machine components such as pipelines for oil and gas transportation, significant components of power plants, e.g. generator tubes boilers, etc. Each structure, apparently, may have different metallurgical defects (cracks, for instance). An aggressive hydrogen environment influence is supposed to accelerate a precipitateness of the fatigue fracture process in the structure component.

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2. The crack propagation due to hydrogen embrittlement

Hydrogen penetrates into material through the material-environment interface due to diffusion process. This process depends on different variables such as temperature, hydrogen concentration, mechanical properties of material etc. There is a number of theories to describe mechanisms of hydrogen penetration into material. Each theory corresponds to appropriate experimental data. Thus, pressure theory, surface adsorption theory, decohesion theory, hydrogen enhanced localized plasticity mechanism, and hydride theory are well known theories of hydrogen embrittlement of solid materials. Eq. (1) describes hydrogen penetration into material in case of unidirectional diffusion and tension of a sample (Panasyuk et al., 1988). Boundary and initial conditions are presented below too.

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} + f\left([\Psi]\right)\frac{\partial C}{\partial x}\frac{\partial \tilde{\sigma}}{\partial x};\ C(0,t) = C^0;\ C(x,0) = C^0 G(x), \tag{1}$$

where x is a coordinate from the crack tip, t is time, $C = C(x,t)$ is hydrogen distribution function, $\tilde{\sigma}$ is stress distribution near the crack tip, C^0 is the current hydrogen concentration in the material-environment interface, $f\left([\Psi]\right)$ is a function of environment and material parameters.

On the other hand, one should refer to the fracture mechanics to describe the crack propagation due to hydrogen embrittlement. Crack, with a half-length l_0 under mode I loading, starts growing when stress intensity factor K_I reaches fracture toughness in a case of homogeneous and solid material.

Mechanical properties of hydrogenated material, such as modulus of elasticity and Poisson's ratio, change regarding the non-hydrogenated material. Consider a homogeneous solid isotropic material and a crack under mode I loading in a body, made from this material and subjected to hydrogen environment.

Mechanical characteristics in the hydrogenated region differ from those of in another part the same body (Tarakanov et al., 2012). Hydrogen penetration into material lattice, for instance, results in decreasing fracture toughness. Therefore, *conditional stress intensity factor* (CSIF) and conditional fracture *toughness* (CFT) $\tilde{K}_I$ and $\tilde{K}_{Ic}$ are introduced instead of K_I and K_{Ic} in the hydrogenated region near the crack tip and a criterion of the crack propagation is described by eq. (2)

$$\tilde{K}_I\left(\tilde{\sigma}^{\infty}, l\right) \geq \tilde{K}_{Ic}\left(\bar{C}_a\right) \tag{2}$$

where $\tilde{K}_I = Y\tilde{\sigma}^{\infty}\sqrt{\pi l}$, $\bar{C}_a$ is an average hydrogen concentration in a *prerupture region a(l)* of the material. This region is much smaller than the hydrogenated one.

Crack growth rate in hydrogenated material depends on a *specific pair*, i.e. *environment and material* used in different experiments. Therefore, authors have introduced a new material-environment characteristic Ω to relate the current hydrogen concentration in the crack tip C^0 (*environment, initial condition of eq. (1)*) to the maximum solubility of the hydrogen in material C^* (*material*), in other words $\Omega = C^0 / C^*$ (Tarakanov et al., 2014).

CFT $\tilde{K}_{Ic}$ versus $\bar{C}_a$ is described by the eq. (3):

$$\left(\left(\tilde{K}_{Ic} - \tilde{K}^*_{Ic}\right)\Big/\left(\tilde{K}^0_{Ic} - \tilde{K}^*_{Ic}\right)\right)^{\alpha_1} + \left(\Omega\cdot\bar{C}_a / C^0\right)^{\beta_1} = 1 \tag{3}$$

where $\tilde{K}^*_{Ic}$ is CFT of the material with uniform hydrogen concentration equals C^0/Ω, $\tilde{K}^0_{Ic}$ is CFT of the non-hydrogenated material, α_1, β_1 - constants.

Crack propagation process is discrete in the given model. It is divided into three main stages:

- The first (incubation) stage may last quite long. It means an initial accumulation of hydrogen near the crack tip in the initial prerupture region. The length of this area depends on the metal lattice. The prerupture region at the first stage of the crack growth is supposed to be defined as function of the metal grain size. The prerupture region increases, when the crack starts growing. The length of the incubation stage depends on the initial concentration of hydrogen near the crack tip, diffusion constant, etc. Incubation stage will complete when the average