

# Crack propagation engineering model: stress intensity dependence of crack growth rate in hydrogen embrittlement material

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**Abstract.** Based on various mechanisms of hydrogen diffusion in metals, different crack propagation models and stress intensity dependence of crack growth rate have been developed. Engineering model of another hydrogen-assisted cracking in metal materials is presented in this paper. This model is based on simultaneous solution of two various problems: diffusion of hydrogen in metal problem and fracture mechanics problem. Special characteristic, which bonds material and environment, is introduced to colligate these two problems together in proposed model.

Engineering model is discontinuous in the present case. The value of crack growth is not a constant. Crack moves out when the concentration of hydrogen in the crack tip reaches maximum permissible value. This magnitude is chosen from the special characteristic mentioned above. The stress intensity dependence of crack growth rate, calculated by authors, has a good correlation with Panasyuk's experimental data.

## Introduction

Hydrogen embrittlement is a form of environmentally assisted failure which is caused by the action of hydrogen often in combination with stress resulting in the reduction of the load bearing capacity of a component. The problem of hydrogen embrittlement in metal alloys is converged in various types of machine components. There are pipelines for oil and gas transportation, significant components of power plants, such as steam generator tubes boilers, steam/water pipe lines among them. Hydrogen embrittlement was main cause accident of fuel cladding in nuclear reactors (Caskey et al 1962), cracking of fossil fuel boilers tubes (Weiss 1993; Speidel & Atrenes 1984; Metals handbook 1987), retaining rings of generator rotors (Speidel & Atrenes 1984), waterside components of condensers (Metals handbook 1987) and in many other components where there is a possibility of hydrogen ingress in the material. These various components are made from metallic alloys, for example, based on Fe, Ni, Al, Ti, Zr, Ta, which are responsive to hydrogen embrittlement.

Hydrogen embrittlement has a pernicious influence on life of the mentioned above machine components. There are many well-known researches and various theories (Panasyuk 1981, Cherepanov 1973, Matvienko 2004), which estimate life of a machine component and structures by means of specific crack propagation engineering models. Therefore crack propagation engineering model of hydrogen embrittlement material research is one of the modern mechanics technical problems. In this paper one of the possible variant of engineering model, which describes the crack growth in hydrogenation structure, is presented. Results, calculated by authors, by means of this model have a good correlation with the experimental data (Panasyuk 1988).

### Crack propagation engineering model: structure

Hydrogen penetrates into material through the material-environment interface due to diffusion process. This process is dependent on different variables: temperature, hydrogen concentration, mechanical properties of material etc. There are many various theories, which describe the mechanisms of hydrogen penetration into material [1-10]. Each theory explains some experimental observations. Pressure theory (Zappfe & Sims 1941), Surface adsorption theory (McMahon C J Jr, Vitek V 1979), Decohesion theory (Oriani & Josephic, 1974), Hydrogen enhanced localized plasticity mechanism (Sirois & Birnbaum, 1992), Hydride theory (Matvienko 2004) are well known theories of hydrogen embrittlement of solid materials. In case of unidirectional diffusion and tension of a sample, hydrogen penetration into material describes by Eq. 1. Boundary and initial conditions are presented below too.

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} + f([\Psi]) \frac{\partial C}{\partial x} \frac{\partial \tilde{\sigma}}{\partial x}; \quad C(x, 0) = C_0(x), \quad C(0, t) = C_0 \quad (1)$$

where  $C = C(x, t)$  - function of hydrogen concentration distribution,  $x$  – coordinate,  $t$  – time,  $\tilde{\sigma}$  - tensile stress,  $f([\Psi])$  - some environment and material parameters.

On the other hand, it should refer to the fracture mechanics to describe the crack propagation engineering model. In case of homogeneous and solid material, crack under mode I loading with a half-length  $l$  (Fig. 1), moves out when stress intensity factor  $K_I$  reaches fracture toughness.

Mechanical properties of hydrogenated material, such as modulus of elasticity and Poisson's ratio, are changed as opposed to non-hydrogenated material, according to [12-15]. Consider a homogeneous solid isotropic material and a crack under mode I loading in a body manufactured from this material.

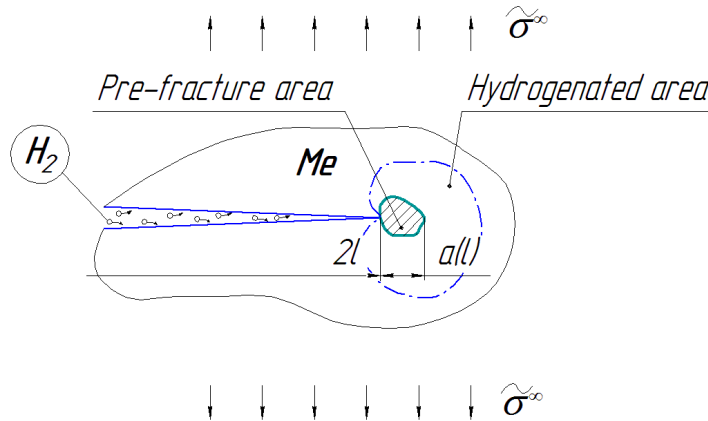


Fig.1. Crack saturated with hydrogen.

Provided that hydrogen penetrates into material through the crack in one direction, area, which is called *hydrogenated area*, will appear. Mechanical characteristics in this area and another part of the same body will be different, as mentioned above. Therefore characteristics  $\tilde{K}_I$  and  $\tilde{K}_{Ic}$  are introduced in the case of hydrogenated material instead of  $K_I$  and  $K_{Ic}$ . We will call it *conditional stress intensity factor (CSIF)* and *conditional fracture toughness (CFT)*. Then criterion of the crack propagation is described by Eq. 2.

$$\tilde{K}_I(\tilde{\sigma}, l) \geq \tilde{K}_{Ic} \quad (2)$$

where  $\tilde{K}_I = Y\tilde{\sigma}^\infty\sqrt{\pi l}$ ,  $\tilde{\sigma}^\infty$  - tensile stress away from hydrogenated area and presented at Fig. 1,  $Y$  - shape factor.

Characteristic  $\tilde{K}_{Ic}$  is a fracture toughness of the even hydrogenated sample with a crack under mode I loading. Suppose  $\tilde{K}_{Ic}$  is a function of hydrogen concentration in the concerned sample. We consider even hydrogenated samples below. But in the case of uneven hydrogenated area, which is presented near the crack tip, it should be noted what concentration used for determination of  $\tilde{K}_{Ic}$ . Average concentration in *pre-fracture area*  $a(l)$ , which is penetrate into hydrogenated area and calculated as function of half-length of the crack  $l$ , is used to determine a required value of  $\tilde{K}_{Ic}$ .

Various experiments [11,14] are showed that crack growth rate in hydrogenated material is depend on specific pair of the environment and material. Therefore it should be taken into account in the case of hydrogenated material crack propagation modeling. New material-environment characteristic  $\Omega$  is introduced for this purpose by the authors. This characteristic connects the current concentration of the hydrogen in the material-environment interface  $C^0$  and the maximum solubility of hydrogen in material  $C^*$ , in other words  $\Omega = C^0 / C^*$  [15,16].

Formula for connection of  $\tilde{K}_{Ic}$  with average concentration in pre-fracture area is presented below:

$$\left(\frac{\tilde{K}_{Ic} - \tilde{K}_{Ic}^*}{\tilde{K}_{Ic}^0 - \tilde{K}_{Ic}^*}\right)^\alpha + \left(\Omega \frac{\bar{C}_a}{C^0}\right)^\beta = 1 \quad (3)$$

where  $\tilde{K}_{Ic}^*$  - CFT for the average concentration in the pre-fracture area equals to  $C^0 / \Omega$ ,  $\tilde{K}_{Ic}^0$  - CFT for the non-hydrogenated pre-fracture area.

Process of crack propagation is discrete in presented engineering model. Crack propagation process is divided into three main stages, according to [11,17]:

- I. The first stage is an initial accumulation of hydrogen near the crack tip in the pre-fracture area. Then with the passage of time  $t^*(a(l_0))$  crack with initial half-length  $l_0$  moves out. This event takes place when the average concentration of hydrogen in the crack tip reaches critical, in other words  $C_{a(l_0)} \xrightarrow{t^*(a(l_0))} \bar{C}_{a(l_0)}$ . Then the value of  $\tilde{K}_I$  reaches the maximum permissible value, which is CFT  $\tilde{K}_{Ic}$ , for the current average concentration of hydrogen in pre-fracture area of the initial crack  $l_0$ . Consequently criterion, presented in Eq. 2, is not satisfied. Thereby initial half-length of the crack  $l_0$  becomes  $l_0 + a(l_0)$  and new pre-fracture area has its own initial distribution of hydrogen concentration;
- II. The second stage is a stable crack growth. After the first growth of the crack the initial concentration in the current pre-fracture area becomes higher than the initial concentration of the previous pre-fracture area initial concentration. Thereby  $t(a(l_0)) \square t(a(l_1))$ . In this case stable crack growth is taken place, till the initial average hydrogen concentration is not greater than critical concentration of the

current pre-fracture area. In other words, this stepwise process of the crack growth is repeated;

- III. The third stage is an unstable crack growth. This stage takes place in the case, when the initial average hydrogen concentration is greater than critical.

### Crack propagation engineering model: description

Construction of the engineering model of stress intensity dependence of crack growth rate is realized by four diagrams modeling, presented in Fig. 2 [17].

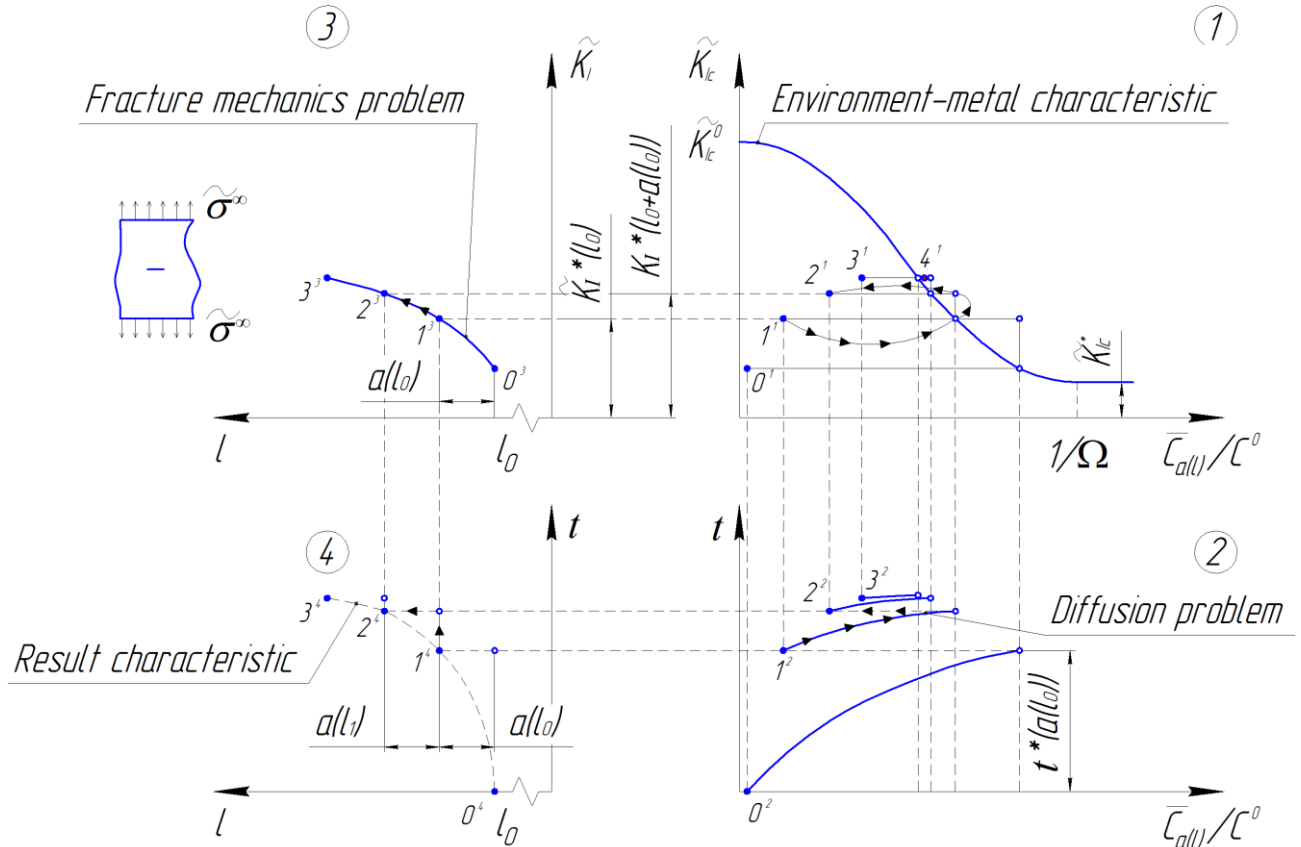


Fig. 2. Theoretical scheme of Crack propagation engineering model.

These four diagrams are result of the diffusion of hydrogen in metal problem and fracture mechanics problem. Diagram with number four, presented in Fig. 2, is determined after the first three diagrams. This diagram allows to determine the relation between conventional stress intensity factor and crack growth rate in hydrogen embrittlement material.

Here is a detail scheme of the crack growth in hydrogen embrittlement material according to presented engineering model. Three stages of the crack growth are described above:

- I. Suppose that in the pre-fracture area of the determined crack presents certain concentration of hydrogen at the initial moment and it is less than critical concentration. Then initial point  $0^1$  at the first diagram will lie as presented in Fig. 2, more to the right than origin of coordinates. Initial point projection on the second and third diagrams gives us points  $0^2$  and  $0^3$ . Point  $0^4$  in the fourth diagram is determined by the coordinates of points  $0^2$  and  $0^3$ . The hydrogen concentration in the crack tip increases due to constant source of the hydrogen in

the crack and its diffusion into the crack tip. Therefore (see diagram 1 at Fig. 2) initial point  $0^1$  moves to the right with the course of time till its path will intercept critical curve at the first diagram. The Average concentration of the hydrogen in the pre-fracture area reaches maximum permissible value at this moment. This value defines by the critical curve, presented in the first diagram. Movement of the 0 point reflects at the second diagram. It is a problem of diffusion hydrogen into the crack tip (pre-fracture area). When the average concentration will reach maximum permissible value, crack will move out. Its length becomes  $2(l_0 + a(l_0))$ . Current time  $t^*(a(l_0))$  is fixed and the point 1 appears at the fourth diagram. Formula for  $t^*(a(l_0))$  is presented below.

$$t^*(a(l_0)) = \frac{\int_{\Phi} \varphi(x)^2 dx}{-\tilde{K}_I f([\Psi])^{\Phi} \frac{\int \varphi'(x)\varphi(x) \frac{dx}{x\sqrt{x}}}{2\sqrt{\pi}} + D \int_{\Phi} \varphi''(x)\varphi(x) dx} \ln \left\{ \frac{\frac{1}{\Omega} \sqrt{\beta} \left[ 1 - \left( \frac{\tilde{K}_I - \tilde{K}_{Ic}^*}{\tilde{K}_{Ic}^0 - \tilde{K}_{Ic}^*} \right)^{\alpha} \right]}{\frac{A_0}{C^0} \varphi(a(l_0))} \right\} \quad (4)$$

where D – diffusion coefficient,  $\varphi(x)$  - coordinate function, which appears after using Galerkin method [18] with orthogonalization of difference on the hydrogenated area  $\Phi$ ,

$$A_0 = C^0 \frac{\int_{\Phi} G(x)\varphi(x) dx}{\int_{\Phi} \varphi(x)^2 dx}, \quad C_0(x) = C^0 G(x).$$

Presented below scheme explains one iteration of the discontinuous process of crack growth for the hydrogen embrittlement material in the case of proposed engineering model. Then point 1 becomes initial point for further iterations.

- II. Abscissa of the point  $1^1$  is bigger than abscissa if point  $0^1$ . This difference is explained by presented further explanation. The average concentration of the hydrogen in the pre-fracture area of the initial crack length  $2l_0$  would be bigger than for the crack length  $2(l_0 + a(l_0))$  according to diffusion process. Than point  $1^1$  reaches the critical curve at the first diagram. This movement of the point  $1^1$  lasts time  $t(a(l_1))$  and point  $2^4$  is introduced at the fourth diagram. Thus, iteration process of crack growth hydrogen embrittlement material is constructed and diagram  $l(t)$  is obtained. Function  $l(t)$  is received by interpolation of known points:  $0^4, 1^4, 2^4$ , etc.
- III. In the Fig. 2 initial concentration of the point 4 is greater than critical concentration. Thereby point  $4^1$  is situated righter the critical curve, described by Eq. 3. This is a signal that in the current example unstable crack growth is begun.

Stress intensity dependence of crack growth rate  $v(\tilde{K}_I)$  is obtained due to known function  $l(t)$ . Points ordinates of function  $v(\tilde{K}_I)$  are resulted from differentiate of  $l(t)$  function. Required abscissas of these points are calculated with a help of first and third diagram. Thus discontinuous engineering model with a goal to construct stress intensity dependence of hydrogen embrittlement material crack growth rate is developed.

## Summary

Engineering model of crack growth rate in hydrogen embrittlement material is constructed due to simultaneously solution of two various problems: diffusion hydrogen in metal problem and fracture mechanics problem. It is possible to use this engineering model for the prediction of the structure life time. Results, calculated by authors with presented model, have a good correlation with experimental data [11].

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