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# Simulation of hydrogen assisted-cracking in terms of its growth phenomenon

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ABSTRACT

Hydrogen-assisted cracking is a nagging problem to take place in various structures like high-strength bolts and steam generator tubes. Here, specific model to describe crack propagation in structure components under cycling and hydrogen environment influence based on the two-parameter hydrogen assisted cracking criterion is presented. The proposed criterion includes the hydrogen concentration in the fracture process zone in the vicinity of the crack tip as well as critical stress intensity factor. The current hydrogen concentration in environment is related to the maximum solubility of the hydrogen in material. In addition the specific expression to define the fracture process zone length is proposed. The developed model allows estimating a durability of structure components under cycling loading and hydrogen environment influence.

## 1. Introduction

Numerous catastrophic failures of the important structure components because of the long-term exposure to aggressive hydrogen environment have been reported [1]. A possible way to decrease the number of these dramatic incidents is to develop the models, which enable predicting a durability of the structure components subjected to aggressive hydrogen environment and external loading. Some codes for Nuclear Power Plants (NPP) structural design allow cracks in dangerous structure components.

Simulation of hydrogen-assisted cracking in terms of its growth phenomenon becomes especially relevant in case of unavailable experimental data about the effect of various parameters which characterize metal grains, manufacturing technology of the structure component under consideration, aggressive hydrogen environment–material pair, susceptibility of the material to hydrogen embrittlement, etc. The new model of crack propagation in hydrogenating structure components under cycling is based on the earlier developed ones.

Essentially, the processing of numerous experimental data shows that there are two principal types of corrosion fatigue cracking models [2], see Fig. 1. In addition, a considered crack under loading (mode I) is also presented in Fig. 1.

The first model to estimate the environmental fatigue crack growth rate $(dl/dN)_{f+d}$ is based on the multiply of the inert growth rate on the factor $Agr$ which is defined using experimental data. This model is called a time-dependent corrosion fatigue [4] (see Fig. 1a).

$$(dl/dN)_{f+d} = Agr \cdot (dl/dN)_f. \tag{1}$$

The second model is based on superposition of the crack growth rates due to the fatigue both in inert environment and in aggressive one. The last one is determined due to static loading (see Fig. 1b) [5]. In other words, a crack growth rate in aggressive environment under cycling loading is defined by the formula:

$$(dl/dN)_{f+d} = \xi_1 \cdot (dl/dN)_f + \xi_2 \cdot (dl/dN)_d, \tag{2}$$

where $\xi_1$ and $\xi_2$ are parameters to be determined using the experimental data.

The processing of certain experimental data by the least square method may be used to define the parameters mentioned above. Herewith, these parameters are valid for the considered environment, stress range, load frequency, and so on. In other words, any change of the environment or stress range, etc. involves conducting a new experiment to define new desirable parameters. These new parameters are used to determine the crack kinetics in the structure component in new initial conditions, for instance, decreased or increased stress range.

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## Nomenclature

| | |
|---|---|
| $Agr$ | multiplication |
| $f$ | load frequency |
| $n$ | Paris–Erdogan power |
| $t$ | time operation |
| $x$ | coordinate from the crack tip |
| $A$ | Paris–Erdogan constant |
| $F$ | function to define crack kinetics due to cyclic loading in aggressive hydrogen environment |
| $R$ | gas constant |
| $T$ | sample temperature |
| $Y$ | crack shape factor |
| $a_0^d$ | initial fracture process length |
| $a_*^d$ | critical fracture process length |
| $l_0$ | initial half-length of the crack |
| $t_{f+d}^*$ | structure component durability |
| $\overline{C}_a$ | average hydrogen concentration in a fracture process zone |
| $C^0$ | current hydrogen concentration in the material–environment interface |
| $C^*$ | maximum solubility of the hydrogen in material |
| $\widetilde{K}_I$ | conditional stress intensity factor |
| $\widetilde{K}_{Ic}$ | conditional fracture toughness |
| $\widetilde{K}_{Ic}^0$ | conditional fracture toughness of non-hydrogenated material |
| $L_{fr}^*$ | critical crack length |
| $V_H$ | partial molar volume of hydrogen in the metal |

*Greek symbols*

| | |
|---|---|
| $\alpha_1$ | toughness factor |
| $\alpha_2$ | fracture region length factor |
| $\beta_1$ | concentration factor |
| $\beta_2$ | crack length factor |
| $\Delta$ | multiplication to account critical crack length |
| $\Delta N_f$ | number of cycles |
| $\zeta$ | multiplication in diffusion equation |
| $\mu$ | Poisson coefficient |
| $\xi_1$ | cyclic loading in inert environment factor |
| $\xi_2$ | static loading in hydrogen environment factor |
| $\tilde{\sigma}(x)$ | stress distribution near the crack tip |
| $\tilde{\sigma}^{\infty}$ | stress far from the crack |
| $\Omega$ | material–environment characteristic |

*Abbreviations*

| | |
|---|---|
| CSIF | conditional stress intensity factor |
| CFT | conditional fracture toughness |

*Other*

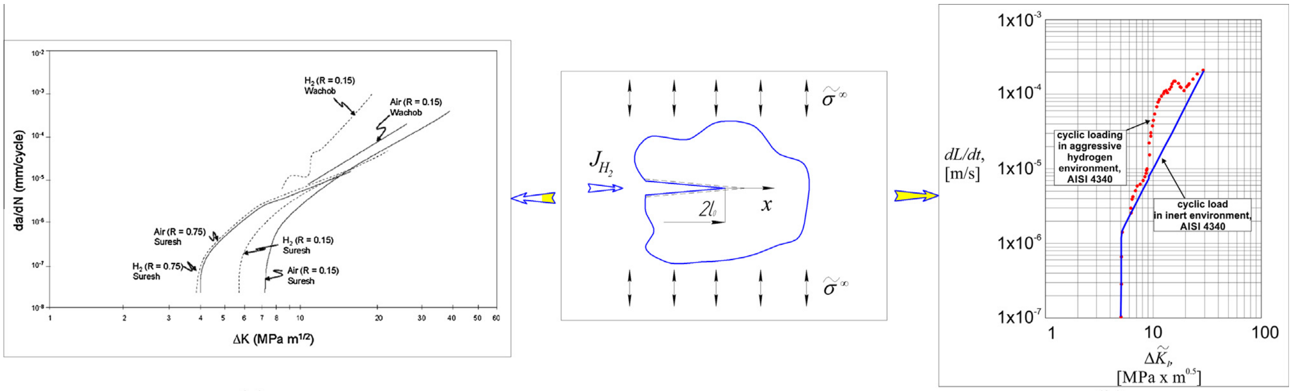
| | |
|---|---|
| $(dl/dN)_f$ | crack growth rate due toi fatigue in an inert environment |
| $(dl/dN)_{f+d}$ | crack growth rate due to fatigue in an aggressive hydrogen environment |
| $(dl/dN)_d$ | crack growth rate due to static loading in an aggressive hydrogen environment |

This way seems to be very inconvenient for engineering analysis. It is impossible to estimate the durability of different components *without numerous experimental observations*. That is why the authors prefer not to use such a way of modeling to determine the crack kinetics in the structure components subjected to hydrogen environment.

In authors' judgment, the time-dependent model (see Fig. 1b) seems to be very interesting. For aggressive environment, the fatigue-cracking curve (see Fig. 1b) illustrates that there are the *independent fracture processes* near the crack tip such as hydrogen embrittlement fracture process and the fatigue one.

The new model has to take into consideration the simultaneous effect of the cyclic load and hydrogen environment on the material near the crack damage accumulation. But with each crack regrowth the prevailing fracture process is chosen from the one caused by fatigue or hydrogen environment influence. However, the hydrogen accumulation must be taken into consideration in crack propagation process throughout. Notably if crack grows due to fatigue, the current hydrogen concentration in the region near the crack has to be taken into selection of the prevailing fracture process for further regrowth of the considered crack. If fatigue causes a crack growth the current hydrogen concentration in the near-crack region has to be taken into consideration to define the prevailing fracture process for further regrowth of the considered crack.

Notwithstanding the great number of various theories to describe the environmental crack fatigue kinetics each model has been developed to current metal–environment pair only [6]. In other words, each model is described by the specific parameters, which are appropriate for the current initial conditions



(a) (b)

**Fig. 1.** Environmental fatigue cracking models [3]. (a) Time-dependent (experimental data from S. Sureh et al. for pipeline steel X70) and (b) cyclically dependent (experimental data from L. Weng et al. for high-strength steel AISI 4340).