

## NUMERICAL SIMULATION OF CRACK PROPAGATION IN A DEGRADED MATERIAL UNDER ENVIRONMENTAL EFFECTS

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**Abstract.** *A numerical model based on the synthesis of Fracture Mechanics and Continuum Damage Mechanics is presented to treat the crack propagation problem in elastic regime, under a mechanical action and an environmental action. The environmental action is characterized by the hydrogen atoms presence in the lattice, which reduces the fracture toughness of many metals and metallic alloys. The crack is loaded in the tensile opening mode, in plane strain state and only two damage types are considered: a mechanical damage produced by a static load and a non-mechanical damage produced by the hydrogen diffusion of the mouth to the crack tip. The crack propagation is considered as the result of the interaction between the balance of forces and the global energy in the crack body-load system and the process of damage accumulation. The equations that describe the evolution of the variables at the crack tip form a non-linear system of ordinary differential equations that is calculated by means of the 4th order Runge-Kutta method. The obtained results, for different concentration conditions, show the influence of the hydrogen concentration in the decrease of the time of growth and crack propagation, what keeps good correlation and consistency with macroscopic observations of the hydrogen embrittlement phenomenon. Additionally, the behavior of the curve of evolution of the stress intensity factor with the time, shows a similar behavior to the one reported in the scientific literature, allowing a better understanding of the process of beginning and crack propagation in aggressive environments, also demonstrating, the validity of the adopted model.*

**Keywords:** *Continuum Damage Mechanics, Hydrogen Embrittlement, Cracks Propagation.*

### 1. INTRODUCTION

The non linear response of the solids, observed in the macro-scale, is a manifestation of irreversible processes that happen in its micro-structure, some of which are originated in micro-defects that constitute the *initial damage* of the material. Depending on the environmental conditions and due to the existence of mechanical loads, even if the global response of the material stays inside in the limits of the elastic regime, the initial damage can develop taking to the formation and growth of microcracks. Environmental factors as the wet air, the seawater and other active media, frequently intensify the beginning and cracks propagation under static or cyclical mechanical loadings. Additionally, an important number of phenomena is related with those processes, showing a very important influence in the decrease of the fracture and fatigue toughness. A typical phenomenon is the *hydrogen embrittlement* that changes the mechanical properties of the metals and metallic alloys, with effects in the decrease of the fracture toughness and in the acceleration of the crack growth (Bolotin, 1999).

The free hydrogen induce structural fails related with the stress corrosion cracking and corrosion fatigue; however, exists additional degradation phenomena, as the voids nucleation and bubbles formation product of the hydrogen diffusion, that can be qualified as microdamage processes and, from a phenomenological point of view, described as the damage produced by purely mechanical actions. Here, the term *hydrogen embrittlement* it is conditional and it includes a quantity of different mechanisms associated with the hydrogen diffusion in metals and metallic alloys.

After the first model proposed by Kachanov, an impressive research activity was realized for the development of viable models for the description of the damage in a great amount of materials as the steel (Celentano & Chaboche, 2007), composites (Maimí, 2006) and others, with the purpose of solving a wide range of connected problems with the degradation of the material properties, such as thermal and inertial effects (Barbosa, 1998), and environmental factors (Duda *et al.*, 2007a; Barbosa *et al.*, 2007). Recently, Duda *et al.* (2007b) formulated a one-dimensional model in the context of the continuum mechanics to simulate deformation, degradation and solute diffusion in elastic solids.

In this article is presented the numerical model proposed by Bolotin & Shipkov (2001), previously used in the numerical simulation of stress corrosion cracking and fatigue corrosion problems, to simulate the crack propagation problem under the effect of a mechanical action defined by a static loading and a non-corrosive environmental action defined by the hydrogen presence in the lattice. The crack in a material body of high strength steel is loaded in the tensile opening mode, in plane strain state and only two damage types are considered: a mechanical damage produced by a static load and a non-mechanical damage produced by the hydrogen. The process is developed in elastic regime.

## 2. MODEL OF BEGINNING AND CRACK GROWTH IN AGGRESSIVE ENVIRONMENTS

In this model, based in a synthesis of the Fracture Mechanics and of the Continuum Damage Mechanics, the crack propagation is considered as the result of the interactions between the conditions of stability of the crack body as a mechanical system and the process of damage accumulation. The model includes the kinetic equations for the accumulation of each damage type, the equation that describes the conditions for the evolution of the crack tip and the equation that describes the influence of the damage accumulation process on the generalized resistance forces.

Will be presented the general theory for the propagation of fatigue cracks developed by Bolotin (1996) and additionally, will be considered a mass transfer model. Their joining with the kinetic equations of damage accumulation, associated to the equilibrium conditions, stability and crack propagation, will make possible the modeling of the growth of a crack submitted to a static load under the effect of the hydrogen.

### 2.1. Cracked body mechanics

A cracked body submitted to a loading and the action of the environment is a special type of mechanical system, whose state is described by a group of L-coordinate (Lagrangian) that describe the displacements field in the body and another of G-coordinate (Griffithian) that describe the sharpening, size and position of the cracks. The changes of the G-coordinate are denominated G-variation and represented for  $\delta a_j$ .

The states of the crack body-loadings system can be classified with regard to the equilibrium and to the stability. The states in what the virtual work is negative for all  $\delta a_j > 0$  are nominated *sub-equilibrium states*. The states in that exists some variation-G where the virtual work is zero and in the remaining the virtual work is negative, are nominated *equilibrium states*; the sub-equilibrium state is also an equilibrium state from the point of view of the classic mechanics. If at least for one of the variations the virtual work is positive, it is said that the system is in a *non-equilibrium state*.

The stability conditions can also be expressed in terms of the virtual work. The sub-equilibrium states evidently are stable, because additional amounts of energy are necessary to change the state of the system for any neighboring state and those sources of energy don't exist inside of the system. The non-equilibrium states cannot be noticed as equilibrium units and therefore, they are unstable. The equilibrium states can be *stables*, *neutrals* or *unstable*.

The *stable equilibrium state* is the most important in the theory of the fracture and fatigue, because it is the typical case of the slow and stable propagation of the crack. A crack will propagate in a stable way when for some G-coordinate,  $\delta_G W = 0$  and  $\delta_G(\delta_G W) < 0$  and still, when the condition  $\delta_G W < 0$  are satisfied for the other.

In terms of *generalized driving and resistance forces*, the virtual work of the G-variation can be represented for:

$$\delta_G W = \sum_{j=1}^m G_j \delta a_j - \sum_{j=1}^m \Gamma_j \delta a_j \quad (1)$$

where  $\delta a_j$  are the G-variations. The generalized driving and resistance forces are  $G_j$  and  $\Gamma_j$  respectively. In terms of those forces, the crack won't grow while the condition  $G_j < \Gamma_j$  be respected. Their growth will begin when  $G_j = \Gamma_j$  and it will turn unstable when for some  $\delta a_k$ ,  $G_k > \Gamma_k$ , happening finally, the fracture of the component. These conditions are valid to model the crack growth and of the final fracture for a static loading including the effect of an environmental phenomenon, as the hydrogen embrittlement.

### 2.2. Hydrogen assisted damage

To model the process of damage accumulation in hydrogen assisted conditions, Bolotin (1999) and Bolotin & Shipkov (2001) uses the simplest, scalar model of damage of Kachanov (1986) and Rabotnov (1979) that characterize the dispersed damage with the scalar field  $\omega=(x,t)$  that is function of the coordinates, of the time, of the number of cycles and of other temporary variables. It is zero in the case where doesn't exist damage and equal to the unit in the case where the material is completely damaged.

Instead of using a simple quantification for the damage, they are introduced a special measure for each damage type and the correspondent kinetic equation that governs its evolution in the time. Same when only actions mechanics are considered, it is differentiated the measures of the damage caused by the static loading of the damage due to other mechanical loadings, as the cyclical. The damage caused by an environmental agent's diffusion is differentiated also of the damage produced by a corrosion process. Therefore, the damage field introduced symbolically for  $\omega=(x,t)$ , does it pass to be represented by a set of scalar damage fields,  $\omega_1(x,t), \dots, \omega_n(x,t)$ .

The disperse damage produced by a static loading in the mode I,  $\omega_s$ , and the disperse damage caused by the hydrogen diffusion,  $\omega_h$ , are shown in Fig. 1. The hydrogen damage is a component that it is added to the total damage magnitude and that it *only depends on the hydrogen concentration at the crack tip*.

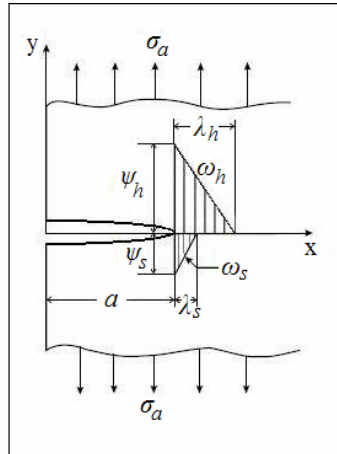


Figure 1. Mechanical and hydrogen damages distribution in an edge crack in the mode I (Font: adapted of Bolotin & Shipkov, 2001).

The evolution of the hydrogen damage and of the static damage at the crack tip, can be expressed for:

$$\frac{d\psi_h}{dt} = \frac{\psi_h^\infty}{c_h} \exp\left(-\frac{c_t}{c_h}\right) \quad (2)$$

$$\frac{d\psi_s}{dt} = \frac{1}{t_c} \left( \frac{\sigma - \sigma_{th}}{\sigma_s} \right)^{m_s} \quad (3)$$

where  $\psi_s$  and  $\psi_h$  are the magnitudes of  $\omega_s$  and  $\omega_h$  at the crack tip;  $\psi_h^\infty$  is the measure of the damage at the crack tip corresponding to the saturation state;  $c_t$  is the evolution of the concentration in the time and  $c_h$  is the stationary concentration of the hydrogen, reached for a stationary crack.  $\sigma$  is the average value of the tensile stress that acts in a considered material point.  $\sigma_s$  characterizes the resistance to the damage produced by the static loading and  $\sigma_{th}$  it is a resistance threshold parameter. The  $m_s$  exponent is similar to the exponents of the equations of fatigue and crack growth rate curves that, under certain conditions, have closed values;  $t_c$  is a time constant whose magnitude can depend on the parameter  $\sigma_s$ , or to be chosen in an arbitrary way.

The stress concentration at the crack tip is related with the effective tip radius,  $\rho$ , and its evolution is governed by several processes, such as the crack growth, the mechanical damage accumulation and the embrittlement. The differential equation for the evolution of the tip curvature radius of a plane crack with length  $a$ , is described for:

$$\frac{d\rho}{dt} = \frac{\rho_s - \rho}{\lambda_a} \frac{da}{dt} + (\rho_b - \rho) \frac{d(\psi_s + \psi_h)}{dt} \quad (4)$$

The first term on the right side of the equation describes the sharpening of the tip due to the crack growth with the rate  $da/dt$  until the magnitude  $\rho_s$  that is the sharp tip radius. The second describes the blunting owed the accumulation of the mechanical damage and the hydrogen damage until the magnitude  $\rho_b$  that is the blunt tip radius;  $\lambda_a$  is a parameter with length dimension.

The last relationship that closes the group of govern equations of the model, interrelates the generalized resistance forces with the damage measures ahead the crack tip. The Specific Fracture Work, that is the energy for area unit that should be spends for the crack growth, is given for:

$$\gamma = \gamma_0 [1 - \chi(\omega_s + \omega_h)^\alpha] \quad (5)$$

where  $\gamma_0$  is the Fracture Specific Work for a no damaged body,  $\chi$  characterize the Residual Fracture Toughness for the damaged material and  $\alpha$  is a material parameter; therefore,  $\gamma = \gamma_0(1-\chi)$  characterize the Specific Work Residual Fracture for a completely damaged material.

In hydrogen embrittlement processes,  $\alpha > 0$  and  $\chi \geq 1$  (Bolotin, 1999). Starting from the Eq. (5) and considering  $\Gamma_0 \equiv \gamma_0$ , can be obtained the *generalized resistance force* for a plane crack,  $\Gamma$ , given for:

$$\Gamma = \Gamma_0 [1 - \chi(\psi_s + \psi_h)^\alpha] \quad (6)$$

### 2.3. Environmental agent transport through cracks

The environmental agent content in the neighborhood of the crack tip is characterized with a scalar variable that depends on a physical time (or a number of cycles) and it is denoted by  $c(t)$  or  $c(N)$ ; that content is the solution concentration.

The crack growth and its path can be considered as boundary conditions for the crack displacement that varies in time due to damage accumulation, tip sharpening and tip blunting, passive formation of films, etc. When the agent's transport happens steadily, almost-stationary models can be accepted. One of those models is given for:

$$\frac{dc_t}{dt} = \frac{c_h - c_t}{\tau_D} + \frac{c_b - c_t}{\lambda_D} \frac{da}{dt} \quad (7)$$

where the first term on the right side represents the diffusion mechanism and the second the effect of the crack propagation. The govern parameters that enter in that equation are the characteristic length of the diffusion zone  $\lambda_D$  and the characteristic time of the diffusion  $\tau_D$ .

The concentration at the crack tip,  $c_t(t)$ , is not usually the same than in its mouth, denoted by  $c_e(t)$ , due to the agent's transport through. The parameter  $c_h$  that characterizes the stationary concentration reach for a stationary crack in the time  $t \gg \tau_D$ , and depends on the entrance concentration and of the length of the crack, is given for:

$$c_h = c_e \left( 1 + \frac{a}{a_\infty} \right)^{-n_a} \quad (8)$$

where  $a_\infty > 0$  and  $n_a \geq 0$  are constant that depend on the material properties and of the environment. The parameter  $c_b$  in Eq. (7) is a characteristic concentration for the fast growth of the crack that close to the length  $\lambda_D$  is connected with the mass transfer. When the crack tip is fixed and the initial condition is  $c_t(0) = c_e$ , the Eq. (8) describes the evolution of the concentration at the tip for:

$$c_t(t) = c_h + (c_e - c_h) \exp\left(-\frac{t}{\tau_D}\right) \quad (9)$$

for  $c_t(0) = 0$ , when the crack tip is initially "dry", the evolution is given for:

$$c_t(t) = c_h + \left[ 1 - \exp\left(-\frac{t}{\tau_D}\right) \right] \quad (10)$$

### 3. NUMERICAL FORMULATION

The purpose of the formulation of this problem is to evaluate the case of the crack propagation through of the mathematical model described previously. The evolutions of damage, crack tip radius and crack length variables, and the generalized resistance forces, form a 1st order differential equations system that is solved through the 4th order Runge-Kutta method.

The stress intensity factor ahead the tip of a crack with length  $a$  is calculated with the following equation:

$$K_1 = Y\sigma_a \sqrt{\pi a} \quad (11)$$

where  $\sigma_a$  is the applied stress and  $Y$  the form factor, whose expression can be found in the book of Bolotin (1999).

To consider the damage accumulation and the crack propagation under a static load and an environmental action, the surface of a plane crack, load in the mode I, is left in contact with a hydrogenated atmosphere.

The concentration at the crack mouth,  $c_e$ , is constant and the static mechanical loading is given by the applied stress. The material is elastic-linear in the whole structure, except in small process areas in the faces of the crack. The body is in plane strain state and the crack length is just a G-coordinate. Therefore, the generalized propagation force  $G_1$  can be calculated for:

$$G_1 = \frac{K_1^2}{E} (1 - \nu^2) \quad (12)$$

where  $E$  and  $\nu$  are the Young's modulus and a Poisson's coefficient, respectively.

In an almost-stationary approach is be considered the rate of crack growth,  $da/dt$ , inside of a small interval of time enough so that the other variables vary very slowly, in other words, treating them as constant in that interval. Therefore, using the Eqs. (2) and (3) and the equilibrium condition give in the Eq. (6), with  $\chi=1$  and  $\Gamma= G$ , one has:

$$\frac{da}{dt} = \frac{\frac{\lambda_s}{t_c} \left( \frac{\sigma_t - \sigma_{th}}{\sigma_s} \right)^{m_s} + \lambda_h \frac{\psi_h^\infty}{c_h} \exp\left(-\frac{c_t}{c_h}\right)}{\left(1 - \frac{G}{\Gamma_0}\right)^{1/\alpha}} \quad (13)$$

To evaluate the mechanical damage, the tension-deformation and concentration fields in the body during the considered process should be known, being able to be used some simple approaches based on an analogy among the stress concentration factor,  $K_t$ , and the stress intensity factor,  $K_I$ . This analogy provides an approximate formula for the stress concentration factor at the tip and for the distribution of the normal stress in its front that can be calculated for:

$$K_t = 1 + 2Y \left( \frac{a}{\rho} \right)^{1/2} \quad (14)$$

$$\sigma = K_t \sigma_a \left[ 1 + \frac{4(x-a)}{\rho} \right]^{-1/2} \quad (15)$$

The Eq. (14) is an extension of the well-know Neuber's formula that calculates the stress concentration factor taking into account the form factor  $Y$ . The Eq. (15) is the simplest of the Shin's empiric equations, where  $(x-a) = \zeta = 10\rho$ . This approach provides good results in plane problems, because that distance is usually enough to esteem the damage field, especially when the distant components of the field can be despised.

The algorithm used in the numerical simulation is show in Fig. 2.

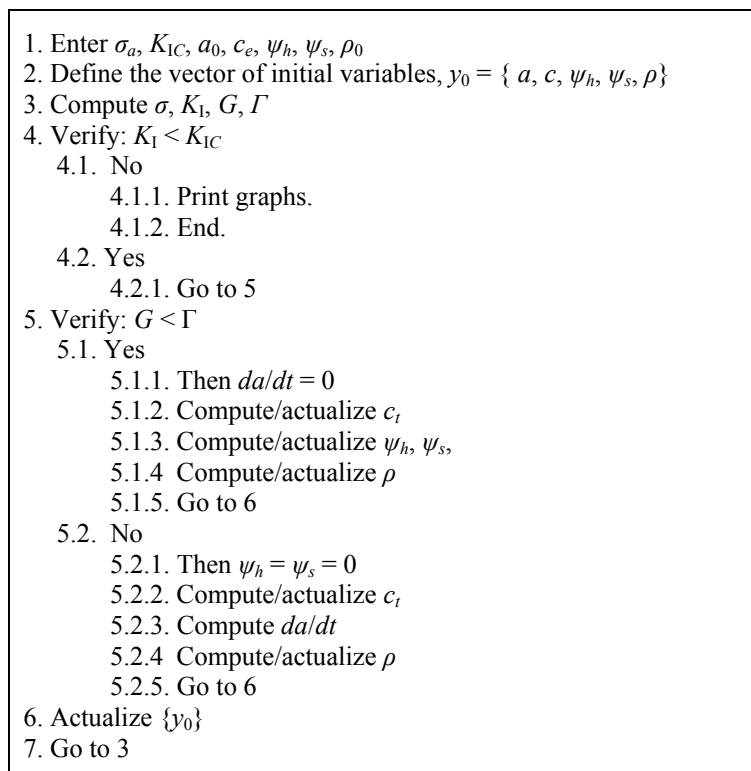


Figure 2. Algorithm used for the resolution of problem.

#### 4. RESULTS AND DISCUSSION

For the evaluation of the applicability of the model, was selected a cracked material body of MARAGING T-250 high strength steel, whose physical and mechanical properties are shown in the Table 1. The material body's geometry is shown in the Fig. 3, whose dimensions are  $l=120\text{mm}$ ,  $w=80\text{mm}$ ,  $b=20\text{mm}$ ; the edge crack's dimensions are: length,  $a=8\text{mm}$  and tip radius,  $\rho=50\mu\text{m}$ .

Table 1. Physical and mechanical properties of MARAGING T-250 steel (Font: ALLVAC, 2000)

$\sigma_r$ (Pa)	$\sigma_y$ (Pa)	$E$ (Pa)	$\mu$ (Pa)	$\nu$ (adim.)	$K_{IC}$ (Pa $\cdot\sqrt{\text{m}}$ )
1.79E+9	1.76E+9	1.86E+11	7.16E+10	0.30	9.81E+7

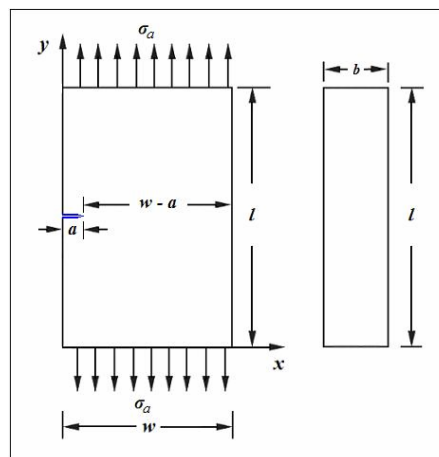


Figure 3. Material body with an edge crack under the applied stress  $\sigma_a$ .

The material parameters used in the simulation and solution of this problem can be found in the Table 2.

Table 2. Material parameters (Font: Bolotin, 1999)

$a_\infty$ (adim.)	$c_b$ (adim.)	$\tau_D$ (s)	$\tau_c$ (s)	$\sigma_s$ (Pa)	$\sigma_{th}$ (Pa)	$\rho_s$ ( $\mu\text{m}$ )	$\rho_b$ ( $\mu\text{m}$ )	$\lambda_D$ (mm)	$\lambda_a$ ( $\mu\text{m}$ )	$\lambda_h$ ( $\mu\text{m}$ )	$\lambda_s$ ( $\mu\text{m}$ )	$\chi$ (adim.)	$\gamma_0$ (kJ/m $^2$ )	$m_s$ (adim.)	$\psi_h^\infty$ (adim.)	$D$ (m $^2$ /s)
1.0	0.5	100.0	5E+3	5E+9	250E+6	10.0	100.0	10.0	100.0	10.0	100.0	1.0	47.1	4.0	0.5	1E-8

The results obtained starting from the application of the model are shown in the following graphs:

Figure 4 display two curves that describe the numeric solutions of the problem of mass transport to the crack tip, given by the Eq. (7), for initial conditions  $c_t(0)=0$  (dry crack) and  $c_t(0)=1$  (wet crack). In the obtaining of those solutions it was assumed that the crack spreads with a constant rate, being ignored the absorption in their faces. The two curves tend to converge quickly for a stationary concentration,  $c_h$ , being the characteristic time for that convergence, of approximately 450s. As it was of waiting, the stationary concentration is reached with more speed when the crack is "wet", for the diffusion started by the generation of a concentration gradient.

Figure 5 display the evolution of the hydrogen concentration at the crack tip soon of the application of the complete model, that it includes mass transfer, damage accumulation and crack growth. It was assumed that the initial damage is null and that the crack is initially "dry". The applied stress of 200 MPa (approximate 11.4% of the yield stress) was maintained constant during all the evolution of the crack.

In the generated curve it can be observed that the agent's transport in the initial stage of the process is quite fast, in response to the speed of diffusion of the hydrogen in the crack. The second stage, where a stable concentration is reached, corresponds to a critical value of that concentration and the beginning of crack propagation. When the growth is more intense, the transport of the hydrogen at the crack tip is hindered, causing the decrease of its concentration, observed in the abrupt decline of the curve in the third stage.

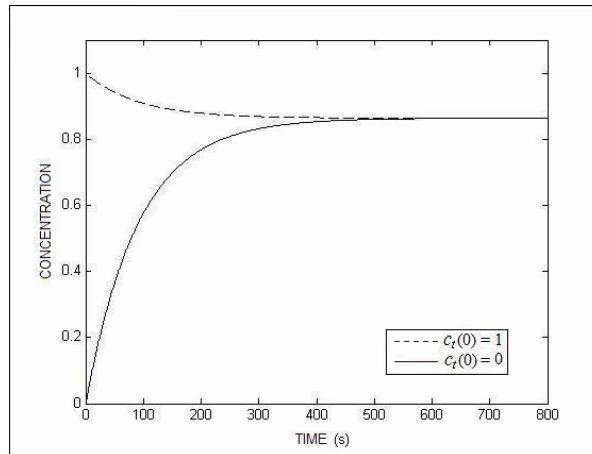


Figure 4. Hydrogen transport to the crack tip. Solution of the mass transport equation.

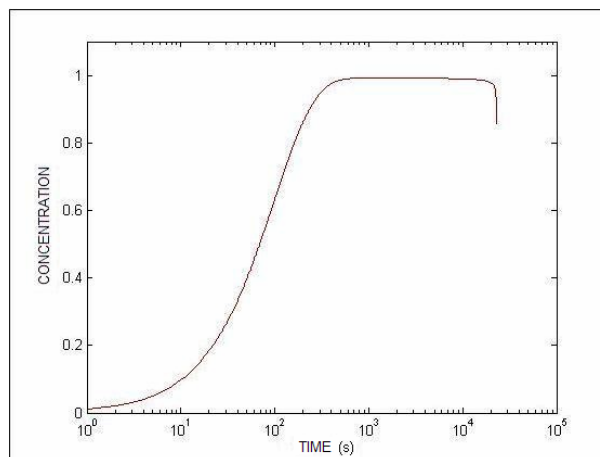


Figure 5. Evolution of the agent's concentration at the crack tip for  $\sigma_a=200\text{MPa}$ .  
 Application of the complete model.

In the Fig. 6 is showed the evolution of the crack growth that is conditioned to the action of the static load and the hydrogen concentration. In it is observed that the initial evolution is very slow and that it hardly suffers alterations in the time; only starting from having lapsed a certain time the crack presents a more and more quick growth, caused by the increase of the driving forces and the decrease of the resistance forces.

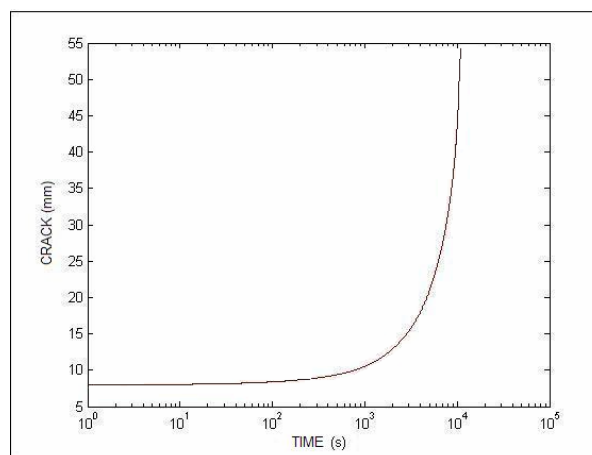


Figure 6. Crack growth evolution for the applied stress  $\sigma_a=200\text{MPa}$  and  $c_e/c_h=1.00$  normalized concentration.

This result is consistent with experimental observations of the crack growth in tensile stress: the critical dimension of the crack,  $a_c$ , is conditioned by the action of the applied load and it will be smaller in the measure in that the load is

bigger. For very high applied stresses, related to the yield limit of the material, the critical dimension will be reached after a growth of some few millimeters (e.g., approximately 3mm for an applied stress of 50% of the yield limit, under the same conditions described in this simulation), for after to occur the instantaneous fracture of the component. In very low levels of the applied load, it simply represents the fail of the structure caused for the crack growth until the limit of the dimensions of the material body, due to the absence of the necessary ligament so that the critical dimension of crack will be reached.

Therefore, under certain load conditions, the highest point in the curves coincides with the critical dimension of the crack, representing the instantaneous fracture of the component due to the generated instability when the resistance forces to the propagation are overcome.

The curves of the Fig. 7 plotted for the same applied load and different hydrogen concentration, show a decrease in the time of beginning of crack propagation and of the final fracture, caused by the increase of aggressive agent's concentration. These results are also consistent with experimental observations of the phenomenon (Gangloff, 2005).

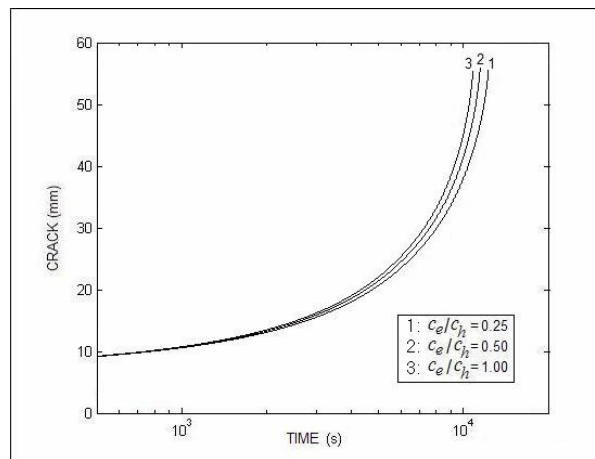


Figure 7. Crack growth evolution for the applied stress  $\sigma_a=200\text{MPa}$  and different  $c_e/c_h$  normalized concentrations.

The graph of the Fig. 8 display the evolution of the effective crack tip radius and it illustrates phenomena that are difficult of be observed directly. The growing part of the curve represents the blunting tip due to damage accumulation process that it is practically instantaneous, conditioned by the fast diffusion of hydrogen. The beginning of the crack growth is represented by the small change of inclination of the growing portion of the curve. When the process of tip blunting is concluded, feels beginning to the process of tip sharpening that also corresponds to the beginning of the crack propagation.

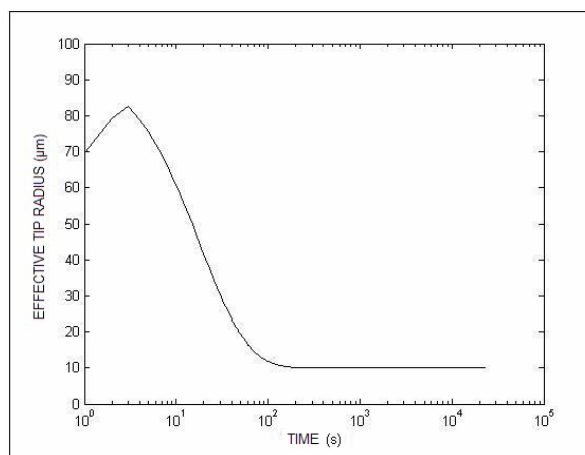


Figure 8. Effective tip radius evolution in hydrogen embrittlement.

In Fig. 9 are shown the curve of evolution of stress intensity factor with the time. The observed behavior, caused by the crack growth, it is to grow until reaching the fracture toughness of the material,  $K_{IC}$  (represented by the horizontal red line), moment in which will happen the fail of the structure. That behavior is consistent with the curves originated in experimental results, obtained in the scientific literature and shown in Fig. 10, and it allows visualizing the process of



the subcritical cracks propagation subjected to loads static mechanics and an environmental action, characterized in this case, for the hydrogen presence in the material.

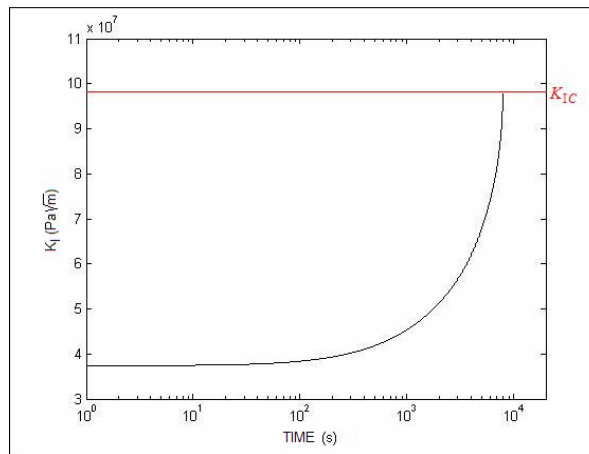


Figure 9. Stress intensity factor evolution for the applied stress  $\sigma_a=200\text{MPa}$ .

In Fig. 10 are shown the evolution curves of the stress intensity factor due to subcritical cracks propagation in environmental assisted conditions obtained in experimental tests for diverse samples and different values of the applied  $K_{I\text{initial}}$  (Brown & Beachem, 1965). In all the cases the fracture occurs when  $K_I$  reaches the fracture toughness value of the material. The phenomenon occurs due to the subcritical crack growth that causes the increase of the stress intensity factor effectively applied. Evidently, while more high it is the value of the  $K_{I\text{initial}}$ , minor will be the necessary time to take the sample until the fracture.

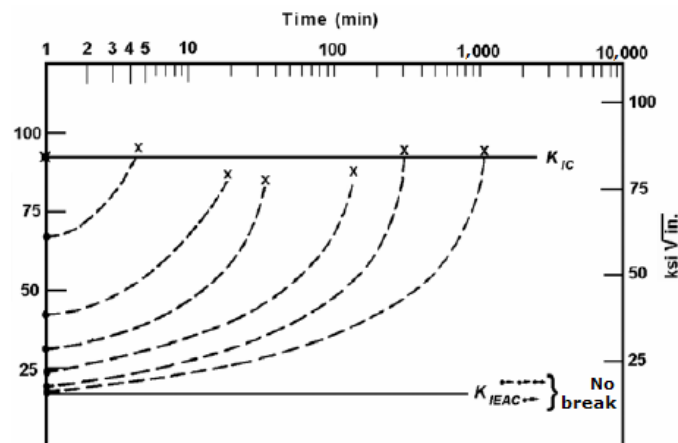


Figure 10. Change in  $K_I$  level associated with subcritical cracks propagation in environmental assisted conditions. Fracture occurs when the  $K_I$  reaches the value of  $K_{IC}$  for any samples (Font: Brown & Beachem, 1965).

These curves keep great likeness with the one obtained in this simulation, starting from a mathematical model that has one of their bases in the principle of subcritical crack growth caused by environmental assistance, i.e., for the degradation process of the material ahead to crack tip caused by the hydrogen action. The obtained results show the validity of the model employed to simulate the crack growth in a material degraded by hydrogen effect.

## 5. CONCLUSIONS

The damage mechanics model adopted shows flexibility and good possibilities of being able to be coupled with models used in the fracture mechanics because both use common parameters, as strain-energy release rate and the stress intensity factor. The obtained results showed a good correlation and a good consistency with the studied phenomena, allowing a better understanding of the beginning and crack propagation processes in environmental assistance conditions.

The study of the crack growth as a result of the damage process due to the application of a static mechanical load and to the action of hydrogen, showed that the time of beginning and crack growth decreases as the agent's

concentration increases, what is consistent with the macroscopic observations of the hydrogen embrittlement phenomenon reported in the scientific literature.

The behavior of the curve of stress intensity factor evolution with the time, obtained in the numerical simulation, shows a similar behavior to curves obtained in experimental test reported in the scientific literature. Similar curves can be obtained in additional simulations with the change of the loading conditions and of the environmental agent's concentration. Those results demonstrate the validity of the model of the beginning and cracks growth adopted.

## 6. ACKNOWLEDGEMENTS

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