EFFECT OF HYDROGEN DIFFUSION IN SOLID PHASE ON FATIGUE CRACK PROPAGATION IN HIGH STRENGTH STEELS - A NUMERICAL SIMULATION

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Abstract. *It is well know that the hydrogen absorption through the metals and metallic alloys lattice causes the degradation of their mechanical properties. The Hydrogen Embrittlement is a degradation process that has shown very significant influences in the reduction of fracture and fatigue resistance of these materials. Under cyclical loading, the crack growth threshold reduction and the fatigue crack growth rate increase are some of the observed effects; they are closely associated with atomic hydrogen diffusion in the solid phase controlled by concentration gradient and stress-strain fields. This paper presents a numerical simulation of the hydrogen atomic diffusion effect on fatigue crack propagation in high strength steels using a model based on a synthesis of fracture mechanics and continuum damage mechanics. The simulation was performed in elastic regimen, in an rectangular steel specimen with an edge crack loaded in the tensile opening mode, in plane strain state, and under the effects of a cyclic mechanical load and an environmental action, characterized by the hydrogen concentration at the crack tip and its diffusion ahead the crack tip. This last process was simulated using the Difference Finite Method. On the other side, was solved the 1st differential equations system formed by the evolution equations of damage, hydrogen concentration, crack tip radius and generalized resistance forces by means of the 4th order Runge-Kutta method. The simulations results shown that under these conditions, the fatigue crack evolution process is enhanced by the hydrogen diffusion in the material, and that the start time of the propagation decreases as its concentration increases. These results show good correlation and consistency with macroscopic observations, providing a better understanding of the fatigue hydrogen embrittlement phenomenon in high strength steels.*

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

1. INTRODUCTION

The effects of work environment on the structural steels are very concern: exist several phenomena associated with the action of environmental effects that cause the degradation of their mechanical properties, such the different damage processes caused by the hydrogen present in moist air, in seawater and other environmental media assets, when it's absorbed into the metallic lattice. A typical phenomenon is the Hydrogen Embrittlement, caused by atomic hydrogen presence in the lattice under applied or residual stresses that induces the reduction on fracture and fatigue resistance of these materials. Under cyclic loading the most important effects are: reduction on the fatigue crack growth threshold (Capelle *et al.*, 2010), the increase of the fatigue crack growth rate (Oda & Noguchi, 2005; Murakami *et al*., 2008), reduction on the fatigue life (Nagumo *et al*., 2003; Kuromoto *et al*., 2004) and reduction in the “tortuosity” of crack growth path (Kanezaki *et al*., 2008). Therefore, from the viewpoint of structural integrity of components in hydrogenated systems, the hydrogen-assisted fatigue analysis is very important.

Hydrogen embrittlement includes several processes developing at various levels of material structure that are closely associated with atomic hydrogen diffusion in the solid phase, such as: penetration of atomic hydrogen into the metal lattice, interaction between atomic hydrogen and dislocations, and hydrogen accumulation in microvoids and microcracks. These processes can be qualified as microdamage processes and, from a phenomenological viewpoint, described as the damage produced by purely mechanical actions (Bolotin, 1999).

Various kinds of theoretical mechanism for hydrogen embrittlement have been proposed so far. Although it is very controversial which mechanism is adequate to explain all phenomena observed in hydrogen embrittlement, it is accepted that the hydrogen concentration near a crack tip plays an important role in hydrogen embrittlement (Takayama *et al.*, 2010). A very important aspect of hydrogen embrittlement is that there exists a transport stage of hydrogen to the sites in structure where degradation occurs. Even if a concentration gradient does not exist, in mechanically loaded systems the hydrostatic stress gradients drive the hydrogen diffusion from distant areas of the crack toward the tip, increasing the local concentration of hydrogen ahead of the crack tip. Thus, along with classical diffusion in solid phase, atomic hydrogen transport controlled by stress should be taken into account (Taha & Sofronis, 2001)

This paper presents a numerical simulation of the effect of hydrogen atomic diffusion on fatigue crack propagation in structural steels using a numerical formulation based on a synthesis of fracture mechanics and continuum damage mechanics proposed by Bolotin & Shipkov (2001). The simulation was performed in elastic regimen, in a rectangular specimen of high strength steel with an edge crack loaded in the tensile opening mode, in plane strain state, and under the effects of a cyclic mechanical load and an environmental action. This last is characterized by the hydrogen diffusion through lattice and its concentration ahead the crack tip.

2. BEGINNING AND CRACK GROWTH IN AGGRESSIVE ENVIRONMENTS

In this model, 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 at the crack tip. 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 cyclic load under the effect of the hydrogen.

2.1. Cracked body mechanics

A cracked body under a mechanical loading and an environment action 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 δa_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 *unstables*.

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 stably way when for some G-coordinate, $\delta_G W = 0$ and $\delta_G(\delta_G W) < 0$ and still, when the condition $\delta_G W < 0$ be satisfied for the other.

From the viewpoint of mechanics of deformable solids, crack initiation and growth is a result of the interaction of two mechanisms: damage accumulation near the crack tip and the general balance of forces and energy in the system cracked body-loading-environment. Therefore, the crack behavior depends on the relationship between the generalized driving force G and the generalized resistance force Γ, and the generalized forces depend on the damage accumulated in the tip zone. G can be associated with the energy release rate in linear fracture mechanics, and Γ with the critical magnitudes of this rate. In terms of these forces, the crack does not grow while the condition $G < \Gamma$ be respected. The crack growth will begin and propagates stably until the next arrest or until the fail when $G = \Gamma$. In the case of $G > \Gamma$, the system is unstable, and the crack to propagates until the fracture of the component.

These conditions are valid to model the crack growth and of the final fracture for a mechanical loading including the effect of an environmental phenomenon, as the hydrogen embrittlement (Bolotin, 1999).

2.2. Hydrogen-assisted damage

To model the process of damage accumulation in hydrogen assisted conditions, is 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 cyclical loading of the damage due to other mechanical loadings, as the static. 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 ω=(x,t), does it pass to be represented by a set of scalar damage fields, $\omega_1(x,t)$, …, $\omega_n(x,t)$.

The disperse damage produced by a cyclic loading in the mode I, ω_f, and the disperse damage caused by the hydrogen, ω_h, are shown in Fig. 1. The hydrogen damage is an additive component of the total damage magnitude and that *depends of the hydrogen concentration ahead the crack tip.*

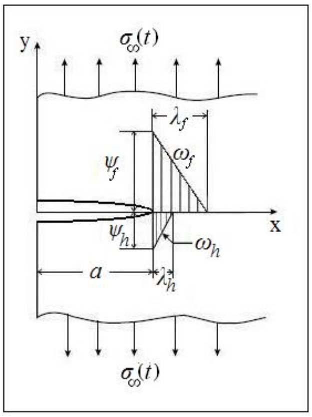

Figure 1. Damages distribution in an edge crack in the mode I (Font: adapted of Bolotin, 1999).

The evolution of the hydrogen damage ahead the crack tip can be expressed for:

$$\frac{d\psi_h}{dt} = \frac{1}{t_c}\left(\frac{\langle c_r \quad c_{th}\rangle}{c_d}\right)^{m_h} \tag{1}$$

where ψ_h is the magnitude of hydrogen damage at the crack tip; c_r is the evolution of the concentration in the time and at the distance r ahead the tip, that varies in the processing zone of hydrogen damage evolution, λ_h; c_{th} is threshold concentration and c_d characterizes the resistance to the hydrogen damage. t_c is a time constant.

The evolution of the cyclical damage at the crack tip can be expressed for:

$$\frac{d\psi_f}{dN} = \left(\frac{\Delta\sigma \quad \Delta\sigma_{th}}{\sigma_f}\right)^{m_f} \tag{2}$$

where ψ_f is the magnitude of cyclic damage at the crack tip and N the number of cycles; $\Delta\sigma$ is the variation of the tensile stress that acts in a considered material point. σ_f characterizes the resistance to the damage produced by the cyclic loading and $\Delta\sigma_{th}$ it is a resistance threshold parameter. In Eq. (1) and Eq. (2) the m_h and m_f exponents are similar to the exponents of the equations of fatigue and crack growth rate curves.

The stress concentration at the crack tip is related with the effective tip radius, ρ, 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 crack with length a, is described for:

$$\frac{d\rho}{dt} = \frac{\rho_s \quad \rho}{\lambda_a}\frac{da}{dt} + (\rho_b \quad \rho)\frac{d(\psi_f + \psi_h)}{dt} \tag{3}$$

The first term on the right side of the equation describes the tip sharpening due to the crack growth with the rate da/dt until the magnitude ρ_s that is the sharp tip radius. The second describes the tip blunting due the accumulation of the total damage until the magnitude ρ_b that is the blunt tip radius; λ_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 *generalized resistance force* for a crack in plane strain state, Γ, is given for:

$$\Gamma = \Gamma_0[1 \quad \chi(\psi_s + \psi_h)^{\alpha}] \tag{4}$$

where Γ_0 is the Fracture Specific Work for a no damaged body; χ characterize the Residual Fracture Toughness for the damaged material and α is a material parameter.

2.3. Hydrogen transport

The environmental agent concentration 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 $c_t(t)$ or $c_t(N)$. 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. A phenomenological approach to the environmental agent's transport from the mouth to the crack tip is given by:

$$\frac{dc_t}{dt} = \frac{\partial c_t}{\partial t} + \frac{\partial c_t}{\partial x}\frac{da}{dt} \tag{5}$$

where the first term on the right side represents the diffusion mechanism in the crack hole, and the second, the effect of the crack propagation.

The hydrogen transport in the solid phase, ahead of crack tip, without considering the trapping, is given for:

$$\frac{\partial c_t}{\partial t} = \frac{\partial}{\partial x}\left(D_s \frac{\partial c_t}{\partial x}\right) - \frac{\partial}{\partial x}\left(B_s c_t \frac{\partial \sigma_h}{\partial x}\right) \tag{6}$$

where the first term on the right side represents the solid-solid diffusion process with the solid diffusion coefficient D_s, and the second, the hydrogen transport controlled by the hydrostatic stress gradient with the coefficient B_s, given for:

$$B_s = \frac{D_s \overline{V}_H}{RT} \tag{7}$$

where $\overline{V}_H$ is the partial molar volume of hydrogen in steel, R is the universal gas constant and T, the absolute temperature. The hydrostatic stress at distance r ahead of crack tip is given for:

$$\sigma_h = \frac{\sigma_{kk}}{3} \tag{8}$$

When the mechanical loading is cyclic, c_t can be interpreted as an average concentration at the crack tip during a cycle. Therefore, the frequency f enters as an additional control parameter because it affects the magnitude of the characteristic concentration for the crack growth, that varies with the "crack breathing" effect due the cyclical loading and the hydrogen is "pumped" for the crack tip (Bolotin & Shipkov, 2001). This effect is included in the model through the following equation:

$$a_\infty(f) = a_\infty(0)\left(1 + \frac{f}{f_\infty}\right)^{n_f} \tag{9}$$

where a_∞ is a characteristic crack length, f_∞ is a characteristic frequency and n_f is a positive parameter.

3. NUMERICAL FORMULATION

The purpose of the formulation of this problem is to evaluate the case of the fatigue crack propagation in a hydrogenated media using the mathematical model described previously. The material is elastic-linear in whole structure, and the crack is loaded in the tensile opening mode. 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 problem of solid-solid diffusion ahead the crack tip is solved by the Difference Finite Method.

The hydrogen concentration at the crack mouth, c_e, is considered constant, and the concentration at the crack tip starts the concentration gradient for diffusion of hydrogen ahead of the crack tip, conversely, the hydrostatic stress leads the hydrogen to the crack tip. The boundary conditions for the diffusion problems in the crack hole, a, and in the process zone of hydrogen damage in front of the crack tip, λ_h, are:

$$c = c_e \quad \text{for} \quad x = 0 \quad ; \quad D\frac{\partial c}{\partial x} = 0 \quad \text{for} \quad x = a$$

$$c = c_t \quad \text{for} \quad x = a + dx \quad ; \quad D_s\frac{\partial c}{\partial x} = 0 \quad \text{for} \quad x = \lambda_h$$

The thickness of hydrogenation film, equivalent to the length of hydrogen damage process zone ahead the crack tip, can be calculated from:

$$\lambda_h = a_0 \frac{D_s}{D_0} \tag{10}$$

where a_0 is the initial crack size and D_0 is the constant of solute/solvent system.

The mechanical loading is given by the cyclic applied stress, $\sigma_\infty(t)$, described for:

$$\sigma_\infty(t) = \sigma_{\infty,m} + \frac{1}{2}\Delta\sigma_\infty \sin 2\pi f\, t \tag{11}$$

where $\sigma_{\infty,m}$ is the average stress, $\Delta\sigma_\infty$ is the stress range and f is the loading frequency, assumed constants during the fatigue life. Since that the body is in plane strain state and the crack length is just a G-coordinate, the generalized propagation force G_I can be calculated for:

$$G_I = \frac{K_I^2}{E}\left(1-\upsilon^2\right) \tag{12}$$

where E is the Young's modulus; K_I is the stress intensity factor ahead the tip of a crack with length a, calculated for the maximum value of applied cyclic stress, $\sigma_{\infty,\max}$, given for:

$$\sigma_{\infty,\max} = \sigma_{\infty,m} + \frac{1}{2}\Delta\sigma_\infty \tag{13}$$

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. 2, whose dimensions are l=120mm, w=80mm, b=20mm; the edge crack's dimensions are: length, a_0=4mm and tip radius, ρ=50μm.

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

σ_r (Pa)	σ_y (Pa)	E (Pa)	υ (ad.)	K_{IC} (Pa·√m)
1.79E9	1.76E9	1.86E11	0,30	9.81E7

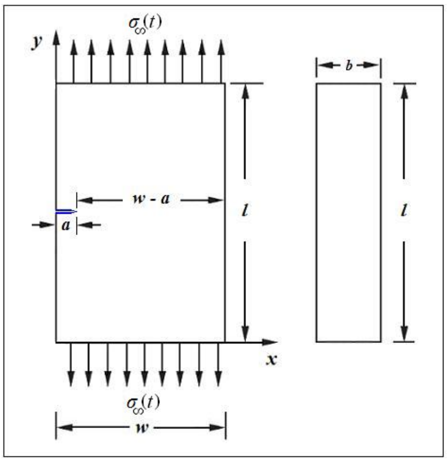

Figure 2. Material body with an edge crack under the applied stress σ_∞.

The material parameters used in the simulation and solution of this problem can be found in the Table 2. The initial value of the specific fracture work for a no damaged body was taken as $\Gamma_0 = 47$ kJ/m^2, which, within the framework of linear fracture mechanics, corresponds to a fracture toughness $K_{IC} = 98$ MPa√m.

Table 2. Material parameters (Font: Sofronis & McMeecking, 1989; Bolotin, 1999)

c_{th}	c_d	τ_D	t_c	$\Delta\sigma_{th}$	σ_f	ρ_s	ρ_b	λ_D	λ_a	λ_f	χ	m_f	m_h	α	D_0	D_s	$\overline{V}_H$	a_∞	f_∞	n_f
(ad.)	(ad.)	(s)	(s)	(Pa)	(Pa)	(μm)	(μm)	(μm)	(μm)	(μm)	(ad.)	(ad.)	(ad.)	(ad.)	(m^2/s)	(m^2/s)	(m^3/mol)	(mm)	(Hz)	(ad.)
0.0	4.0	1E2	1·E2	12.5E7	5E9	10.0	100.0	10.0	100.0	100.0	1.0	1.0	2.0	1.0	1.6E-6	1.27E-8	2.0E-5	100.0	1.0	1.0

The results obtained starting from the application of the model for $\sigma_{\infty,m}$= 600 MPa, $\Delta\sigma_\infty$ = 200 MPa e $f = 10^{-2}$ Hz are shown in the following graphs:

Figure 3 display two curves that describe the numeric solutions of the problem of mass transport from the mouth to the crack tip, given by the Eq. (5), for initial conditions $c_t(0)$=0 (dry crack) and $c_t(0)$=1 (wet crack). Fig. 4 show the numeric solutions for the same problem and initial conditions including the “crack breathing” effect due to application of cyclic loading. In the obtaining of those solutions it was assumed that the crack grow with a constant rate, being ignored the absorption in their faces. The four curves tend to converge quickly for a stationary concentration being the characteristic time for that convergence, different for the two considerate cases. As it was waited, the convergence time is smaller when is taken the “crack breathing” effect, due to that the hydrogen is “pumped” to the tip.

That particularity of the hydrogen transport when the structure is under a cyclical loading is one of the reasons for that the damage accumulation process be more accentuated compared with environmental processes under static loading. The consequences are of great relevance, because there is an important effect on the rate of degradation of the material properties, resulting in the decrease of fatigue resistance.

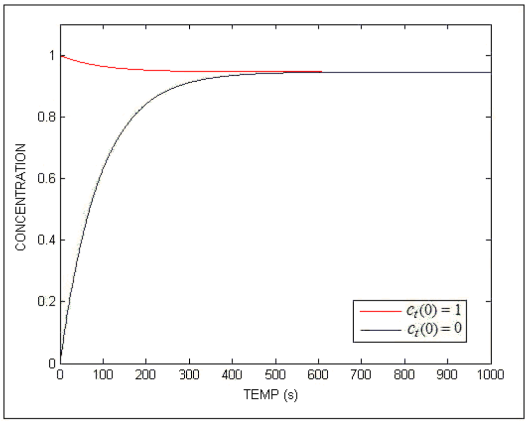

Figure 3. Hydrogen concentration at the crack tip. Solution of mass transport from the mouth to the crack tip without including the “crack breathing” effect.

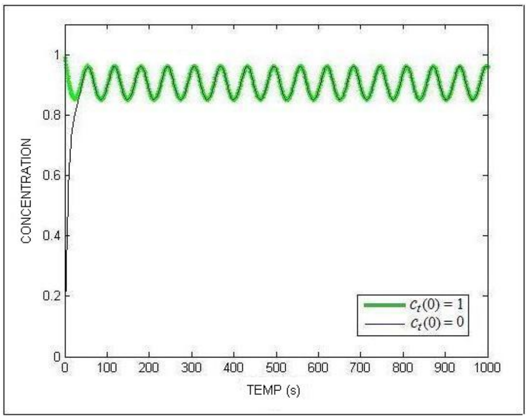

Figure 4. Hydrogen concentration at the crack tip. Solution of mass transport from the mouth to the crack tip including the “crack breathing” effect.

Figure 5 and Figure 6 show the distribution of the hydrogen in the damage process zone ahead to the crack tip, with and without the inclusion of the stress gradient. In them it is observed clearly that when the stress is applied, the hydrogen migrates for the close area to the crack tip, intensifying the degradation process of material ahead of the crack tip. As it will be seen later, the effects are the reduction of fracture toughness and the acceleration of the crack growth.

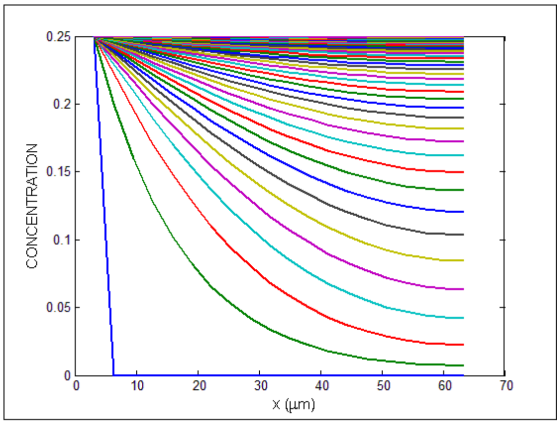

Figure 5. Hydrogen transport in the damage process zone ahead the crack tip without considering the diffusion by stress gradient.

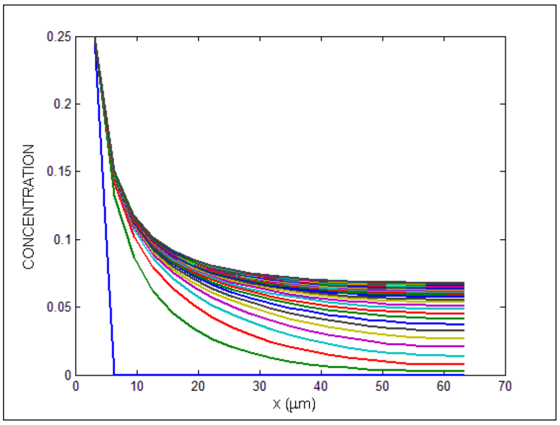

Figure 6. Hydrogen transport in the damage process zone ahead the crack tip considering the diffusion by stress gradient.

In Figure 7 is shown the damage distribution along the damage process zone, where is observed that the close area to the crack tip is the more degraded. This last keeps a direct relationship with the hydrogen concentration in that region, associated to the applied loading.

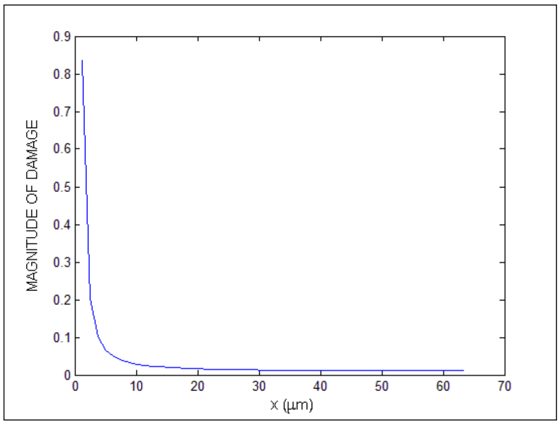

Figure 7. Damage distribution along the process zone.

Figure 8 display the evolution of the hydrogen concentration at the crack tip after application of the quasi-full model, which considers only mass transfer in the hole crack (without diffusion ahead the crack tip), damage accumulation, and crack growth. It was assumed that the initial damage is zero and that the crack is initially "dry". The applied stress was maintained constant during the crack evolution process. In the curve it can be observed that the hydrogen transport in the initial stage of process is quite fast, in response to the speed of the hydrogen diffusion in the crack hole. The second stage, where a stable concentration is reached, corresponds to a critical value of that concentration and the onset of crack propagation. When growth becomes more intense, the transport of hydrogen to the crack tip is hindered, causing a decline in concentration observed at the end of the third stage. The instability observed, mainly in the second phase of the curve, is related to the "pumping effect" in the diffusion process in the hole of the crack, which was included in the transport equation (Eq. (5)).

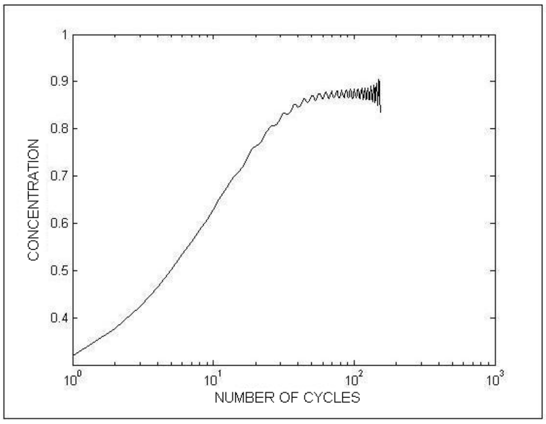

Figure 8. Evolution of the hydrogen concentration at the crack tip. Application of the model without considering solid-solid diffusion ahead the crack tip.

Figure 9 shows the evolution of the concentration of hydrogen at the crack tip after application of the full model, where was included mass transfer with diffusion ahead the crack tip. Can be observed that the hydrogen transport in the initial stage is less quick that the situation described previously, and that the increase of concentration at third stage is not hindered. The situation is motivated by the diffusion of hydrogen that enters to the crack tip and is driven to distant regions ahead the crack tip. The net concentration of hydrogen ahead the crack tip is due to the hydrostatic stress that hinders the movement of the hydrogen that takes it away from the tip, according to Eq. (6).

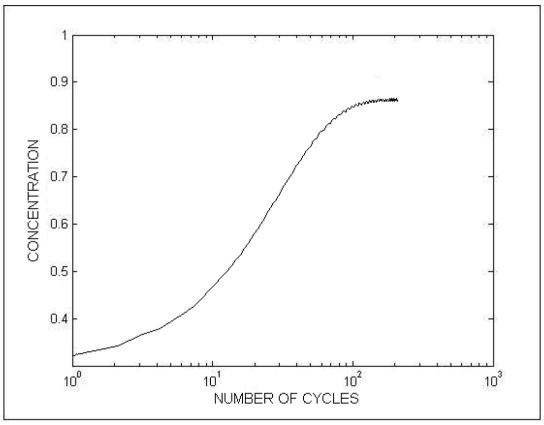

Figure 9. Evolution of the hydrogen concentration at the crack tip. Application of the full model.

In Figure 10 is showed three curves that correspond to the evolution of fatigue crack growth for three situations: first, when the structure is under the action of cyclic loading and hydrogen without considering the solid-solid diffusion ahead of the crack tip; second, when is considered the solid-solid diffusion ahead of crack tip, and third, when the structure is only under cyclic loading. In the first two curves is observed that only at a small range of number of cycles, the crack evolution is very slow and does not undergo major changes; only from a certain level it starts growing until it reaches a smooth increasing speed higher. In the third curve, the range where the crack evolution is not changed is much higher, but the growth is much more abrupt and higher rates of growth are achieved more quickly. The highest point of the three curves represents the onset of unstable propagation and final fracture of the component. As expected, when the structure is under the action of hydrogen and cyclic loading, the initiation of growth and stable crack propagation occurs much sooner than when only applies to cyclic loading. The result is a corresponding reduction of fatigue life of the material.

The difference among the first two curves is that the latter is more real, because the concentrations at the tip of the crack obtained in the first situation are artificially more high, due to is not considered the diffusion process The result, after application of the full model, is a adjusted curve, which theoretically is closer to a real curve.

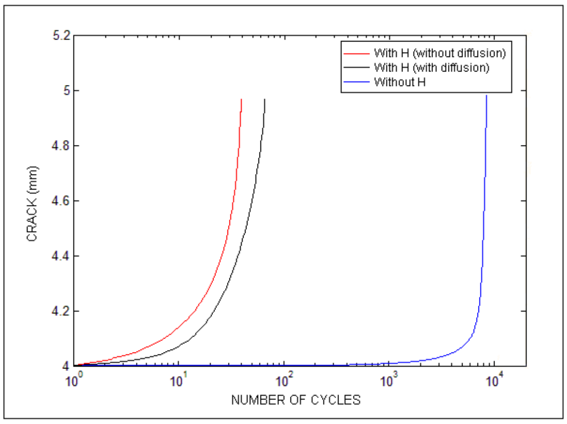

Figure 10. Fatigue crack growth evolution for specimens without hydrogen and with hydrogen for the applied stress $\sigma_{\infty,m}$ =600MPa and c_e/c_h =1.00 normalized concentration.

These results are consistent with the curves originating from experimental observations of the fatigue crack growth under hydrogen assistance. Two curves obtained in the scientific literature (Kanezaki *et al.*, 2008), shown in Fig. 11, allows visualizing the process of the subcritical cracks propagation subjected to cyclic loads and an environmental action, characterized in this case, for the hydrogen presence in the material.

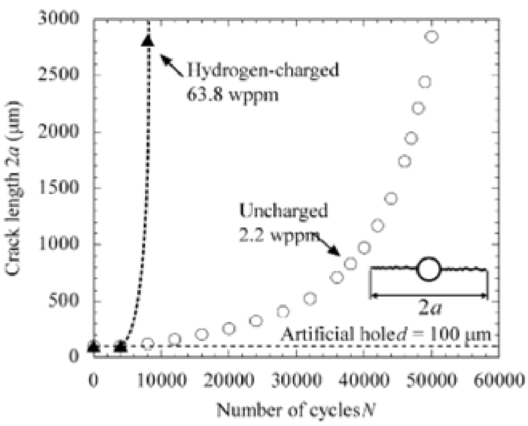

Figure 11. Influence of hydrogen charging on fatigue crack growth from100µm hole in austenitic stainless steels SUS304 (Font: Kanezaki *et al.*, 2008)

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 simulation of the crack growth as a result of the damage process due to the application of a cyclic mechanical load and to the action of hydrogen, showed that the time of beginning and crack growth decreases as the agent's concentration increases, and decreases dramatically when compared with the effect of cyclic loading only. It is believed that the decrease in time is due to the decrease in threshold stress intensity factor for fatigue crack growth, highly influenced by the environment. The described situations are, therefore, the result of material degradation due to the combined action of mechanical loading and the action of hydrogen, which is consistent with macroscopic observations of the hydrogen embrittlement phenomenon reported in the scientific literature.

The results showed good consistency with observations of the phenomenon, well described in scientific literature, allowed a better understanding of the process of initiation and propagation of fatigue cracks under hydrogen assistance, allowed to infer the model validation for the conditions and hypotheses outlined in the problem.

6. ACKNOWLEDGEMENTS

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