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MODELING OF THE SLOW STRAIN RATE AND CONSTANT LOAD CORROSION TESTING OF AUSTENITIC STEELS USING CONTINUUM DAMAGE MECHANICS

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Abstract. T*he present work is concerned with an alternative methodology for modeling* both *SSR (Slow Strain Rate) and CL (Constant Load) testing based upon Continuum Damage Mechanics. The modeling accounts for the stress corrosion cracking of the specimen in corrosive environments. In this macroscopic approach, besides the classical variables (stress, total strain, plastic strain), an additional scalar variable related with the damage induced by plasticity and stress corrosion is introduced. An evolution law with environment dependent parameters is proposed for this damage variable. The model accounts for the stress corrosion effect through a reduction of the mechanical resistance of the specimen induced by the damage variable. The theoretical model was compared with the curves obtained experimentally in different acid solutions at room temperature showing a good agreement. The alloy/environments system was 304 austenitic stainless steel/acid chloride solutions.*

Keywords: *Slow Strain Rate Test, Constant Load Test, Damage Mechanics, Stress Corrosion Cracking, Stainless Steel*

1. Introduction

Stress corrosion cracking remains as one of the main limitations for the use of austenitic stainless steels on chemical and petrochemical industries. The combined effect of corrosion and mechanical stress imposed on the material is extremely complex. The mechanisms proposed to explain microscopically the cracking initiation and propagation processes are not able to elucidate all aspects of the phenomenon in different metal/environment systems[1]. Therefore attempts to predict this phenomenon in macroscopic scale models are advisable.

Slow strain rate and constant load tests are widely used on stress corrosion cracking research as the basic experimental technique to promote the incidence of cracking and to determine the ranking of susceptibility of different alloys in several corrosive environments. With this methodology, however, the assessment of "threshold values" to be used as design parameters is not a simple task in the present state of the art of materials research. This limitation induces the use of the SSR and CL testing only as "go-no go" test for materials selection. Some basic information required, for instance, time to failure in service, can not be inferred from this approach. The most important reason for the limitation described is the complexity of stress corrosion mechanism that involves the conjoint action of mechanical and electrochemical processes.

Despite the lack of definition of a basic mechanism for stress corrosion cracking, the evaluation of the susceptibility to cracking is a basic requirement for safe and economic operation of many types of equipment. This objective is accomplished by the execution of a set of laboratory tests that simulates the conditions of SCC incidence. In this situation, slow strain rate testing is the most important technique used to rank the susceptibility of different materials in a specific environment. Constant load and constant displacement tests are frequently used as an auxiliary technique in order to obtain more detailed information about the resistance of the material. These tests, however, do not provide basic parameters to be directly used in engineering design or to determine the “safe life” of equipment. This limitation can be explained as a consequence of the nonexistence of a model to interpret the macroscopic behavior of the material registered during the SCC tests.

The most interesting possibilities of macroscopic modeling of stress corrosion testing are provided by Fracture Mechanics and Continuum Damage mechanics. In the case of Continuum Damage Mechanics, the damage (geometrical discontinuities induced by the deformation and corrosion processes) is taken into account through an internal variable related with the loss of mechanical strength of the system due to the damage (geometrical discontinuities induced bye the deformation process). This approach introduces the possibility of considering important physical phenomena like hardening, plasticity, viscoplasticity and corrosion.

2. Experimental procedures

Slow strain rate (SSR) and constant load (CL) tests were performed at different acid environments with chloride ions. In these tests it was used an AISI 304 stainless steel with the chemical composition presented in Table 1.

Element	**C**	**S**	**Ni**	**Si**	**Mo**	**Mn**	**Cr**	**Fe**
Wt %	0,06	0,005	8,03	0,47	0,03	1,40	18,95	Bal.

Table 1: chemical composition of the 304 austenitic stainless steel

The steel was normalized at 1050°C for 30 minutes in argon atmosphere and water-quenched. The surface of the samples was ground to grit 600 with emery paper. After surface preparation, the samples were washed with distilled water and alcohol, and dried with hot air. The round specimens were designed according to ASTM E-8 standard with 4 [mm] nominal diameter and 16 [mm] gauge length. The samples were loaded with 1.5 yield stress in the constant load testing and the strain rate used on slow strain rate testing was 3.0x10^{-6} s^{-1}. The aerated solutions were prepared from 1 M sodium chloride acidified with 1 M chloride acid to adjust the desired pH. All the measurements were performed at room temperature under free corrosion potential.

3. Modeling

In this paper, a theoretical analysis, developed within the framework of continuum damage mechanics [2], is performed to provide a better understanding of the slow strain rate test. All the proposed equations can be developed from thermodynamic arguments that are not presented here due to the limited space. A more detailed discussion may be found in [3-5].

Consider as a system a bar-type tension specimen with gauge length L_o and cross-section A_o submitted to a prescribed elongation ΔL. The basic idea is to introduce a macroscopic variable $D \in [0, 1]$, related to the loss of mechanical strength of the system due to the damage (geometrical discontinuities induced bye the deformation and corrosion processes). If D = 1, the bar is "virgin" and, if D = 1, it is "broken" (it can no longer resist to mechanical loading). The following model is proposed to describe the coupling between elasto-plasticity and the damage induced by the corrosion phenomenon

$$\sigma = (1 - D)\, E\, (\varepsilon - \varepsilon_p) \tag{1}$$

$$Y = (1 - D)\, [v_1 (1-\exp(-v_2 \varepsilon_p)) + \sigma_p] \tag{2}$$

$$\frac{d\varepsilon_p}{dt} = \left\langle \frac{\sigma - Y}{K} \right\rangle^N \tag{3}$$

$$\frac{dD}{dt} = \frac{\eta\sigma^2}{E(1-D)^a}\,\frac{d\varepsilon_p}{dt} + \left(\frac{S\sigma}{(1-D)}\right)^R \tag{4}$$

where $\langle x \rangle = \max\{0,x\}$ and the variables σ, ε, ε_P are defined as follows

$$\sigma = F/A;\ \varepsilon = (\Delta L/L_o);\quad \varepsilon_P = \ (\Delta L_P/L_o);\ \Delta L = \Delta L_E + \Delta L_P \tag{5}$$

with ΔL_E being the elastic or reversible part of ΔL and ΔL_P the plastic or irreversible parcel of ΔL. These variables coincide, respectively, with the nominal axial stress, the axial strain and the axial plastic strain while the system is submitted to a uniaxial state of stress. In the presence of macro cracks the real state of stress is no longer uniaxial and the variables σ, ε, ε_p must be interpreted as global parameters. Y is an auxiliary variable related to the hardening induced by the process of plastic deformation. E, K, N, v_1, v_2, σ_p, η and a are material constants and S, R parameters which depend on the material and environmental conditions. Equations (1), (2) will be called the sate laws and equations (3), (4) the evolution laws. Normally the evolution laws are used considering a "virgin" initial state: ε_p (t=0) = 0 and D (t=0) = 0. From equations (2) and (3) we have:

$$\frac{d\varepsilon_p}{dt} = 0 \ \text{ if } \sigma \le Y \tag{6}$$

$$\sigma = (1 - D)\, [v_1 (1-\exp(-v_2 \varepsilon_p)) + \sigma_p] + K(d\varepsilon_p/dt)^{1/N}\ ,\ \text{if } \sigma > Y \tag{7}$$

The variable Y is the elastic limit which is affected by the plasticity phenomenon (that causes an increasing of the elastic limit $\Rightarrow \frac{dY}{d\varepsilon_p} \geq 0 \ \ \forall \ D \in [0,1], \ \forall \ \varepsilon_p \geq 0$) and by the damage (that causes a decreasing of the elastic limit $\Rightarrow \frac{dY}{dD} \leq 0 \ \ \forall \ D \in [0,1], \ \forall \ \varepsilon_p \geq 0$). Equation (7) with D=0 is a classical expression for elasto-viscoplastic materials [2]. The experimental identification of the parameters K, N, v_1, v_2 and σ_p is reasonably simple and it is described in this reference. The parcel $[v_1(1\text{-exp}(\text{-}v_2\varepsilon_p))+\sigma_p]$ models the non linear relation between the elastic limit Y and the plastic deformation ε_p. This expression is verified experimentally and is found in literature [2].

The term $K(d\varepsilon_p/dt)^{1/N}$ in equation (7) is related to the viscosity-hardening and is responsible for the dependency of the elastic limit on the rate of plastic deformation. The constant σ_p corresponds to the elastic limit when the strain rate is very small ($\frac{d\varepsilon_p}{dt} \to 0$).

The variable D is related to the reduction of the free energy of the mechanical system due to the damage induced by the deformation process and corrosion. From (2), it is simple to verify that $Y \to 0$ when $D \to 1$. It is also possible to verify from (7) that $\sigma \to 0$ when $D \to 1$. The evolution law (4) for the damage variable may be divided in two parts: one related to the plastic deformation and other related to the stress corrosion

$$\frac{dD}{dt} = \frac{dD_{plast}}{dt} + \frac{dD_{cor}}{dt} \ ; \ D_{plast} = \frac{\eta\sigma^2}{E(1-D)^a}\left(\frac{d\varepsilon}{dt}\right)^P \ ; \ D_{cor} = \left(\frac{S\sigma}{(1-D)}\right)^R \tag{8}$$

where D_{plast} is the plastic damage and D_{cor} is the corrosion damage. If the rate of plastic deformation is equal to zero, there is no evolution in the plastic damage

$$\frac{dD_{plast}}{dt} = \frac{\eta\sigma^2}{E(1\text{-}D)^a}\ \frac{d\varepsilon^P}{dt} = 0 \tag{9}$$

3.1. Modeling of slow strain rate tests

In SSR testing, the deformation of the specimen is prescribed: $\varepsilon(t) = \alpha\ t$ (α is the strain rate). Using equations [1 - 4] it is possible to verify that, in this case, the plastic deformation ε_p and the damage variable D at a given time instant t can be determined by solving the following system of ordinary differential equations:

$$\frac{d\varepsilon_p}{dt} = \left\langle \frac{(1-D)\,E\,(\alpha t - \varepsilon_p) - (1-D)\,[v_1(1\text{-exp}(\text{-}v_2\varepsilon_p))+\sigma_p]}{K} \right\rangle^N \ ; \ \varepsilon_p(t=0) = 0 \tag{10}$$

$$\frac{dD}{dt} = \frac{\eta((1-D)\,E\,(\alpha t - \varepsilon_p)\,)^2}{E(1-D)^a}\ \frac{d\varepsilon_p}{dt} + \left(\frac{S(1-D)\,E\,(\alpha t - \varepsilon_p)}{(1-D)}\right)^R \ ; \ D(t=0) = 0 \tag{11}$$

If ε_p and D are known at a given instant t, the stress σ and the variable Y can also be obtained using the following equations:

$$\sigma = (1-D)\,E\,(\alpha t - \varepsilon_p) \tag{12}$$

$$Y = (1-D)\,[v_1(1\text{-exp}(\text{-}v_2\varepsilon_p) + \sigma_p] \tag{13}$$

3.2. Modeling of constant load tests

In a constant load test, the value of the stress σ ate every instant t is known: $\sigma(t) = \sigma_o \quad \forall t$. Using equations [1 - 4] it is possible to verify that, in this case, the plastic deformation ε_p and the damage variable D at a given time instant t can be determined by solving the following system of ordinary differential equations:

$$\frac{d\varepsilon_p}{dt} = \left\langle \frac{\sigma_o - (1 - D)\,[v_1(1\text{-}\exp(\text{-}v_2\varepsilon_p))+\sigma_p]}{K} \right\rangle^N \;;\; \varepsilon_p(t = 0) = 0 \qquad (14)$$

$$\frac{dD}{dt} = \frac{\eta\sigma_o^2}{E(1\text{-}D)^a}\,\frac{d\varepsilon_p}{dt} + \left(\frac{S\sigma_o}{(1\text{-}D)}\right)^R \;;\; D(t = 0) = 0 \qquad (15)$$

If ε_p and D are known at a given instant t, the stress σ and the variable Y can also be obtained using the following equations

$$\varepsilon = \frac{\sigma_o}{(1 - D)\,E} + \varepsilon_p \qquad (16)$$

$$Y = (1 - D)\,[v_1(1\text{-}\exp(\text{-}v_2\varepsilon_p) + \sigma_p] \qquad (17)$$

Supposing that the plastic damage is negligible in a constant load test, it is possible to find the solution of the differential equation that governs the damage evolution

$$\frac{dD}{dt} = \frac{dD_{cor}}{dt} = \left(\frac{S\sigma_o}{(1\text{-}D)}\right)^R \;;\; D(t{=}0){=}0 \Rightarrow D(t){=}1\text{-}\left[1\text{-}\left(\frac{t}{\frac{1}{R+1}\left(S\sigma_o\right)^{-R}}\right)\right]^{\frac{1}{R+1}} \qquad (18)$$

Since rupture occurs when D=1, it is possible to compute the time t_r until the rupture

$$D{=}1\text{-}(1\text{-}t/t_r)^{1/R+1} \quad \text{with} \quad t_r = \frac{1}{R+1}(S\sigma_o)^{-R} \qquad (19)$$

The evolution law for the stress corrosion damage is similar to the creep damage law proposed by Kachanov [6].

In low strain rate tests in austenitic steels, the damage variable increases slowly until almost the end of the test ($t = t_r$) when it increases very fast until rupture (D=1), as it is shown in figure 1.

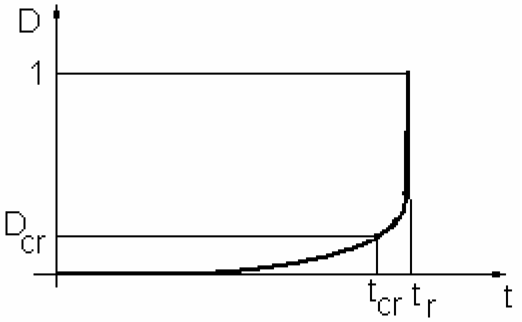

Figure 1: Stress corrosion damage evolution in a slow strain rate test.

If this kind of damage behavior is observed, It is usual to consider a critical value D_{cr} of the damage variable, beyond which the evolution to the value D=1 is so fast that it can be considered instantaneous. If, in a conservative approach, the failure is considered to happen when $D=D_{cr}$, the following expression is obtained

$$D{=}1\text{-}\left[1\text{-}\left(\frac{t}{t_{cr}+\frac{(1\text{-}D_{cr})^{(R+1)}}{R+1}(S\sigma_o)^{-R}}\right)\right]^{\frac{1}{R+1}} \quad \text{with} \quad t_{cr} = \frac{1\text{-}(1\text{-}D_{cr})^{(R+1)}}{R+1}(S\sigma_o)^{-R} \qquad (20)$$

Equation (19) or (20) allows to obtain curves of the damage evolution for constant load tests under different conditions. Examples of this curves are shown in the next section. It is interesting to remark that the parameters R and S are not independent and that they are related with the time t_{cr} through relations (19). The experimental identification of the parameters R and S for a given pH is made from one low strain rate test and one constant load test. From the constant load test it is obtained the value t_{cr}. Since σ_o and t are fixed, the parameters R and S will be related through equation (19). Hence, it is only necessary to identify the value of R in a tensile test.

To understand how the model describes the evolution of the deformation in a constant load test, it is necessary to take the derivative of equation (1)

$$\begin{aligned} \sigma = (1 - D)\, E\, (\varepsilon - \varepsilon_p) \Rightarrow \frac{d\sigma}{dt} &= (1 - D)\, E\, \left(\frac{d\varepsilon}{dt} - \frac{d\varepsilon_p}{dt}\right) - \frac{dD}{dt} E\, (\varepsilon - \varepsilon_p) \\ \Rightarrow \frac{d\varepsilon}{dt} &= \frac{1}{(1 - D)\, E} \frac{d\sigma}{dt} + \frac{\sigma}{(1 - D)^2\, E} \frac{dD}{dt} + \frac{d\varepsilon_p}{dt} \end{aligned} \tag{21}$$

Since σ is a constant and hence $\frac{d\sigma}{dt} = 0$, it comes that

$$\frac{d\varepsilon}{dt} = \frac{S^R (\sigma_o)^{R+1}}{E(1-t/t_r)^{(R+2/R+1)}} + \frac{d\varepsilon_p}{dt} \tag{22}$$

If the plastic damage is negligible, using equation (19) it is possible to verify that the first term in the right side of equation (22) can be written in the following alternative form

$$\frac{\sigma_o}{(1 - D)^2\, E} \frac{dD}{dt} = \left(\frac{\sigma_o}{(1 - D)^2\, E}\right)\left(\frac{S\sigma_o}{(1-D)}\right)^R = \frac{S^R (\sigma_o)^{R+1}}{E(1-D)^{R+2}} = \frac{S^R (\sigma_o)^{R+1}}{E(1-t/t_r)^{(R+2/R+1)}} \tag{23}$$

Neglecting the plastic damage, the rate of plastic deformation (the second term in the right side of equation (22)) is given by the following equation obtained from (2), (3) and (19

$$\frac{d\varepsilon_p}{dt} = \left\langle \frac{\sigma_o - Y}{K} \right\rangle^N = \left\langle \frac{\sigma_o - (1-t/t_r)^{1/R+1}\,)\ [v_1(1-\exp(-v_2\varepsilon_p))+\sigma_p]}{K} \right\rangle^N \tag{24}$$

If σ_o is smaller than σ_p, the rate of plastic deformation will be zero. If σ_o is bigger than σ_p, the rate of plastic will be different than zero. In this case, the term $[v_1(1-\exp(-v_2\varepsilon_p))+\sigma_p]$ will increase until a maximum value $[v_1+\sigma_p]$. The term $(1-t/t_r)^{1/R+1}\,)$ will decrease until zero. It is possible to verify that this modeling allows the description of three typical regions of the corrosion elongation curve I (see figure 2):

$$\text{I}: \frac{d^2\varepsilon_p}{dt^2} < 0\ ,\ \text{II}: \frac{d^2\varepsilon_p}{dt^2} = 0\ ,\ \text{III}: \frac{d^2\varepsilon_p}{dt^2} > 0 \tag{25}$$

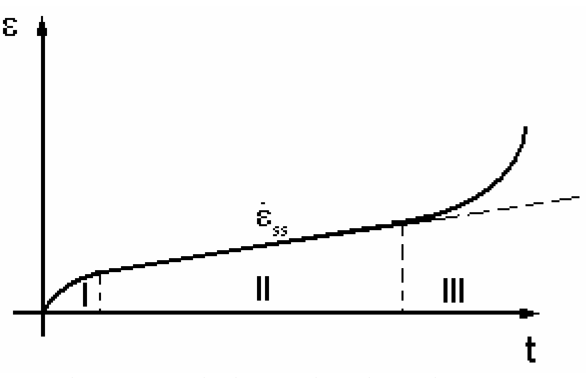

Figure 2: Typical corrosion elongation curve

Using (22) – (24) it is possible to obtain the following expression for the elongation rate

$$\frac{d\varepsilon}{dt} = \frac{S^R(\sigma_o)^{R+1}}{E(1-t/t_r)^{(R+2/R+1)}} + \left\langle \frac{\sigma_o - (1-t/t_r)^{1/R+1}\,)\,[v_1(1\text{-}\exp(\text{-}v_2\varepsilon_p))+\sigma_p]}{K} \right\rangle^N \qquad (26)$$

Since the damage variable (both the plastic and corrosion damage) is approximately equal to 1 during most of the test, it is possible to obtain the following analytical expression for the steady state elongation rate $\dot{\varepsilon}_{ss}$

$$\dot{\varepsilon}_{ss} = \left\langle \frac{\sigma_o - [v_1+\sigma_p]}{K} \right\rangle^N \qquad (27)$$

The influence of the steady state elongation rate and its relation with the time to failure has been object of different recent papers [7].

As it is shown in the next section, the corrosion elongation curve is very well described by this model steady state elongation rate, time to failure, etc.).

4. Comparison with experimental results

To evaluate the adequacy of the model presented, samples of stainless steel were tested in constant load test and slow strain rate test, and the experimental results were checked with the model. The model parameters identified experimentally for the alloy described in Table 1 are given by: E= 193000 MPa; K = 95,336 (MPa s)$^{1/N}$, N = 165; a = 52; η = 0,013 (MPa h)$^{-1}$. Based on experimental observations, it was adopted the following critical value for the damage variable: D_{cr} = 0.13.

$$S = \begin{Bmatrix} 1/472.52\ (\text{MPa h})^{-1/R}\ \text{- pH} = 0{,}0 \\ 1/1358.63\ (\text{MPa h})^{-1/R}\ \text{- pH} = 0.5 \\ 0\ \text{- air} \end{Bmatrix} \quad R = \begin{Bmatrix} 35\ \text{- pH} = 0{,}0 \\ 6.5\ \text{- pH} = 0.5 \\ 0\ \text{- air} \end{Bmatrix} \qquad (28)$$

The systems of ordinary differential equations formed by equations (10), (11) (slow strain rate test) and (14), (15) (constant load test) were solved using embedded 4th order Runge-Kutta Cash-Karp method with 5th order error estimate. The variable order Runge–Kutta method is a family of explicit Runge–Kutta formulas. Each member of the family consists of a fifth-order formula that includes embedded formulas of orders from 1 to 4. A proper order formula is chosen by calculating the solution at several different orders before the full Runge–Kutta step is computed. The detailed algorithm is included in the work of Cash and Karp [8].

4.1. Constant load tests

In this section, the results of constant load tests performed in different environments are compared with the model previsions. Figure 3 shows the theoretical and experimental corrosion elongation curves at a constant stress (σ_o=375 MPa) obtained in the air, and in aerated solution prepared from 1 M NaCl acidified with 1 M HCl to adjust the desired pH to 1.0 and 0.5. The model prevision is in very good agreement with the experimental results.

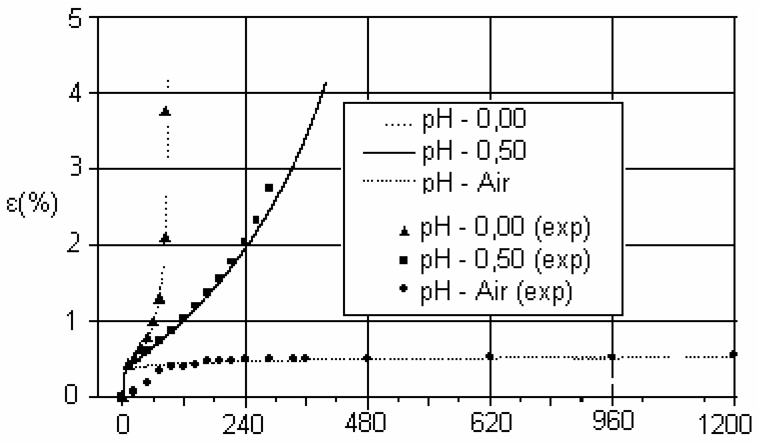

Figure 3: stress elongation curves in different environments. σ_o=375 MPa.

Neglecting the plastic damage and using equation (20) with a critical damage $D_{cr} = 0.13$, it is possible to obtain the fracture time t_r for constant load tests with σ_o=375 MPa for different pH's. Table 2 shows the fracture time obtained experimentally for different pH's and the theoretical value t_r.

t_r	experimental	model
pH=0,50	372 h	372 h
pH=0,00	90,28 h	90 h

Table2: experimental and theoretical fracture time.

Figure 4 shows the theoretical σ_o - log(t_r) curve. The behavior is almost linear, which is in agreement with experimental observations [7] for austenitic stainless steel in acid environments at room temperature.

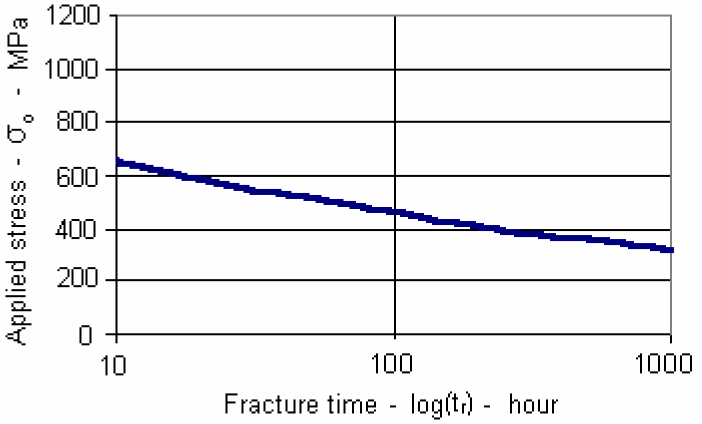

Figure 4: Relative stress corrosion cracking resistance. Model prevision.

4.2 Slow strain rate tests

In this section, the experimental stress-strain curves obtained in slow strain rate tests performed in different environments are compared with the model previsions. Figure 5 shows the theoretical and experimental stress-strain curves with $\dot{\varepsilon}$ = 10XE^{-6} obtained in the air and in aerated solution prepared from 1 M NaCl acidified with 1 M HCl to adjust the desired pH to 1.0 and 0.5. The model prevision is also in very good agreement with the experimental results.

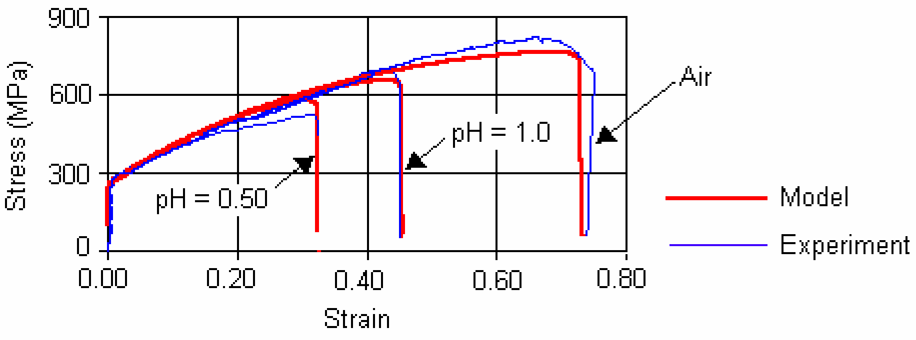

Figure 5: Stress–strain curves for different pH's. $\dot{\varepsilon}$ = 10XE^{-6}.

Figure 6 shows the damage evolution computed for the SSRC tests performed in the air and in a solution with pH = 0.50. From this calculation it is possible to observe that the corrosive environment strongly affects the damage evolution. This parameter shows explicitly the evolution of damage due to stress corrosion along the testing.

The damage variable presents a stable evolution until a critical value $D_{cr} \approx 0.13$. After this critical value is reached, the damage increases abruptly until the limit value D=1 corresponding to the fracture. At this final stage, the plastic damage is responsible for the abrupt increase of the damage rate.

Although the good agreement between model prevision and experiments in constant load tests, in the case of slow strain rate tests the results are not very good for small values of pH, as it is shown in figure 7. Such limitation of the model in the environment with pH = 0.00 may be explained by the more uniform distribution of the cracks induced by SCC which modify the damage and subsequently the mechanical behavior as a whole..

In environments with higher values of pH, the alloy is virtually unattacked over most of the surface, while fine cracks progress through it. Nevertheless, in a typical SSRT with pH =0.0, around 60 cracks were found for a gauge length of 16mm besides an even corrosion.

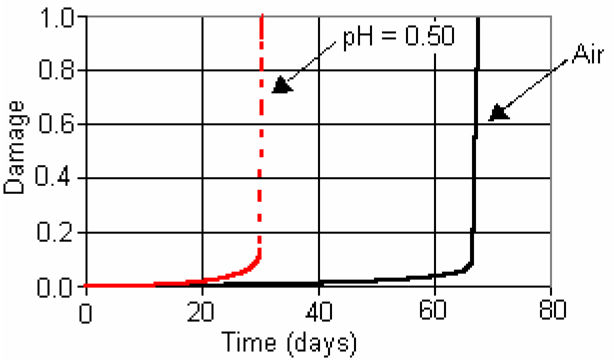

Figure 6 : Damage evolution for different environments.

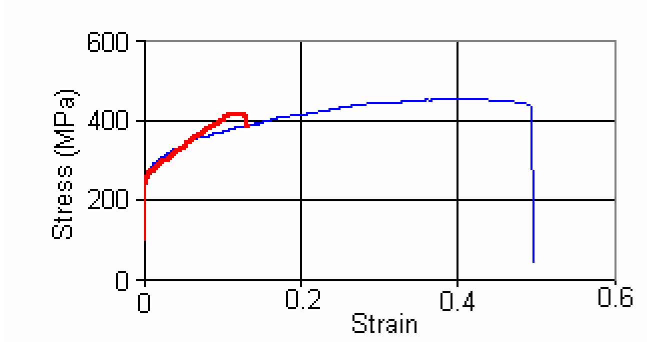

Figure 7: Stress–strain curve, pH = 0.0. $\dot{\varepsilon}$ = 10XE^{-6}.

Such a great density of cracks requires a gradient enhanced damage theory such as proposed by Chimisso [9]. In this theory, an evolution law with an additional tern must be used

$$\frac{\partial D}{\partial t} = \frac{\eta\sigma^2}{E(1-D)^a}\dot{\varepsilon}_p + \left(\frac{S\sigma}{(1-D)}\right)^R + \underbrace{C\frac{\partial^2 D}{\partial z^2}}_{\text{additional term}} \tag{29}$$

where z is the axial coordinate and C a material parameter. The smaller is C, the most localized is the damage. However, the earlier proposed evolution law is suitable to model the majority of experimental results presented here, regardless the specific micro-mechanism that takes place in the interface metal-electrolyte.

5 Sensitivity Analysis

Sensitivity analysis is a commonly methodology of studying the effect of parameter variations on the behavior of mathematical models in various branches of mechanical field. This procedure used in conjunction with traditional digital simulations resulting in an added insight into behavior of models. An important requirement in parameter estimation is that the sensitivity coefficients should not be of small magnitude, and when two or more parameters are estimated simultaneously, their sensitivity coefficients must be linearly independent over the experimental time domain.

In the present work, we analyzed the scaled sensitivity coefficients, which are defined as

$$X_s(t) = \beta_s \frac{\partial \varepsilon(t)}{\partial \beta_s} \text{ , s= 1, 2, ...,6} \tag{30}$$

to analyze CL test and

$$X_s(t) = \beta_s \frac{\partial \sigma(t)}{\partial \beta_s} \text{ , s= 1, 2, ...,6} \tag{31}$$

to study SSR test. In both equations, β_s are the parameters used in the present sensitivity analysis and may be one of these six parameters: $\{S, R, K, N, v_1, v_2\}$. As it can be observed in equations. (30) and (31), the scaled sensitivity coefficients have all the same units of ε (in CL test) or σ (in SSR test). The sensitivity coefficients were calculated using a numerical approximation. Therefore, equation (30) was calculated as

$$\frac{\partial\varepsilon(t)}{\partial\beta_s}=\frac{\varepsilon(\beta_1,\cdots,\beta_s+\Delta\beta_s,\cdots,\beta_6)-\varepsilon(\beta_1,\cdots,\beta_s-\Delta\beta_s,\cdots,\beta_6)}{2\Delta\beta_s}\quad,\ s=1,2,\ldots,6 \qquad (32)$$

and equation (31) as

$$\frac{\partial\sigma(t)}{\partial\beta_s}=\frac{\sigma(\beta_1,\cdots,\beta_s+\Delta\beta_s,\cdots,\beta_6)-\sigma(\beta_1,\cdots,\beta_s-\Delta\beta_s,\cdots,\beta_6)}{2\Delta\beta_s}\quad,\ s=1,2,\ldots,6 \qquad (33)$$

Similar shapes (time dependence) of sensitivity coefficients for two different parameters indicate that their effects on the model response are similar, being, therefore, impossible to tell them apart. Larger sensitivity coefficients are related to better chances of obtaining good estimates. See the curves related to the constant load test to observe that v_1 and v_2 are linearly dependent and, indeed, have higher effects on model. R and S have the biggest magnitude at the end of the test.

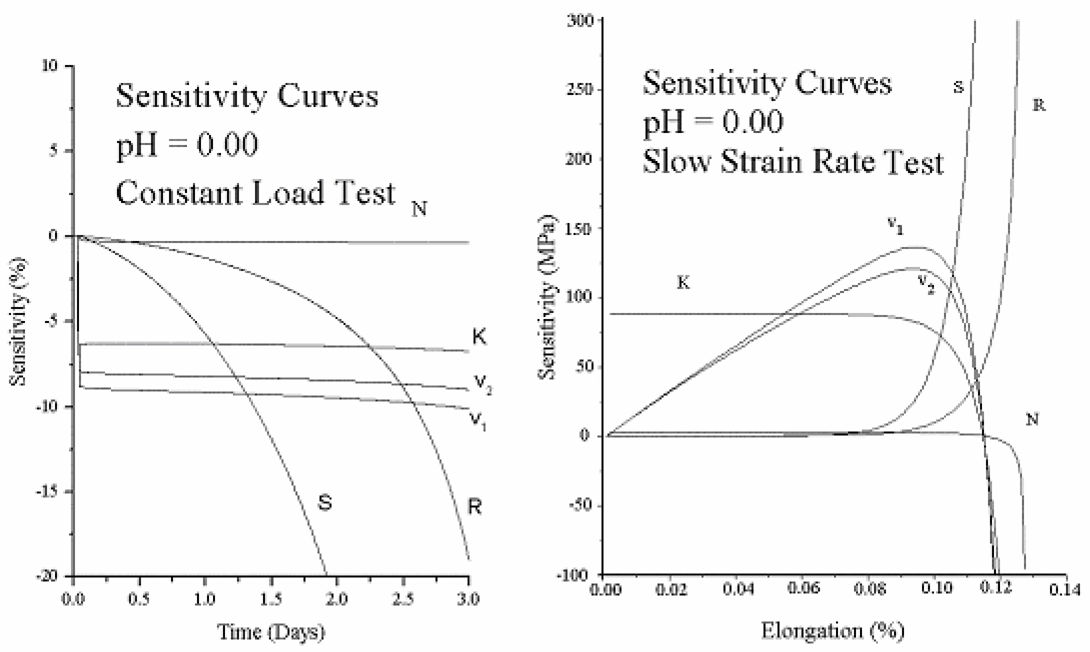

Figure 7: Sensitivity curves for constant load test and slow strain rate test. pH = 0.0

This analysis is important to demonstrate which parameters are really important in each models and consequently these parameters should be measured or determined carefully.

6. Concluding remarks

The present paper is a step towards the modeling of stress corrosion cracking phenomenon in metallic materials by using Continuum Damage Mechanics. A simple continuum damage model is proposed to describe SSR and CL tests in austenitic stainless steels. The model previsions are in good agreement with experiments where the alloy/environments system is AISI 304 austenitic stainless steel/acid chloride solutions. The results obtained by experiment and predicted parameters time of fracture and total elongation are practically identical. The agreement between theory and experiment is very good in tests performed in air or in environments with pH value equal or greater than 0.50. For pH = 0.00, due to the more uniform distribution of corrosion cracks and even simultaneous uniform corrosion, the simulation of a slow strain rate test underestimates the elongation of the specimen at the rupture. Such limitation of the model may probably be surpassed by using an alternative approach based on gradient enhanced theory. The effective development of corrosion damage models not only agree with experimental results as a whole, but explicit the actual damage during the usual constant load and slow strain rate tests.

7. References

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