67º congresso 2012 abm
67th abm international congress
ISSN 1516-392X

DOES NOTCH SENSIBILITY EXISTES IN ENVIRONMENTALLY ASSISTED CRACKING?[1]

Jaime Tupiassú Pinho de Castro[2]
Julio Cesar Costa Leite[3]
Rodrigo Vieira Landim[4]

Abstract

Re-initiation lives of fatigue cracks repaired by the stop-hole technique, tested by introducing small holes at the tip of deep cracks on modified SE(T) specimens, have been satisfactorily predicted using their properly calculated notch sensitivity factor *q*, considering the notch tip stress gradient influence on the fatigue behavior of mechanically short cracks. This is an indispensable detail, since traditional *q* estimates are only applicable to semi-circular notches, whereas the elongated slits resulting from the repair of long cracks can have *q* values which also depend on their shape, not only on their tip radius. Based on this evidence, an extrapolation of the criterion for acceptance of short cracks is now proposed for environmental assisted cracking.

Key words: Short cracks; Non-propagating cracks; Environmental assisted cracking.

EXISTE SENSIBILIDADE AO ENTALHE EM TRINCAMENTO INFLUENCIADO PELO AMBIENTE?

Resumo

A vida de re-iniciação de trincas de fadiga reparadas por furos de contenção, testada após introduzir furos na ponta de trincas profundas em corpos de prova SE(T) modificados, foi satisfatoriamente prevista utilizando seu fator de sensibilidade ao entalhe *q* correto, considerando a influência do gradiente de tensão em torno da raiz do entalhe no comportamento à fadiga de trincas mecanicamente curtas. Este detalhe é indispensável, pois as estimativas tradicionais de *q* somente são aplicáveis a entalhes semicirculares, enquanto os entalhes alongados possuem valores de *q* que dependem do formato e não somente do raio da sua ponta. Baseado nesta evidência, uma extrapolação do critério de aceitação de trincas curtas é proposto para trincas induzidas pelo meio ambiente.

Palavras-chave: Trincas curtas; Trincas não-propagantes; Trincamento influenciado pelo ambiente.

[1] *Technical contribution to 67th ABM International Congress, July, 31th to August 3rd, 2012, Rio de Janeiro, RJ, Brazil.*
[2] *Mechanical Engineer, Ph.D., Professor of the Mechanical Engineer Department, PUC-Rio.*
[3] *Petroleum Engineer UFBA, Petroleum Engineer, Petrobras.*
[4] *Mechanical Engineer, INT.*

ISSN 1516-392X

1 INTRODUCTION

The notch sensitivity $0 \leq q \leq 1$ relates the linear elastic (LE) stress concentration factor (SCF) $K_t = \sigma_{max}/\sigma_n$, to $K_f = 1 + q\cdot(K_t - 1) = S_L(R)/S_{Lntc}(R)$, its corresponding fatigue SCF at $R = \sigma_{min}/\sigma_{max}$, which quantifies the actual notch effect on the fatigue strength of structural components.[1] σ_{max} and σ_{min} are the maximum and minimum LE stress at the notch root caused by σ_n; σ_n is the nominal stress that would act at that point if the notch did not affect the stress field around the notch; S_L and S_{Lntc} are the fatigue limits measured on standard (smooth and polished) and on notched test specimens (TS), respectively. It is well known that q can be associated with the relatively fast generation of tiny non-propagating fatigue cracks at notch roots if $S_L/K_t < \sigma_n < S_L/K_f$. The notch sensitivity q can be predicted from the fatigue behavior of short cracks emanating from notch tips, using relatively simple but sound mechanical principles, which do not require heuristic arguments, or arbitrary data-fitting parameters.[2,3]

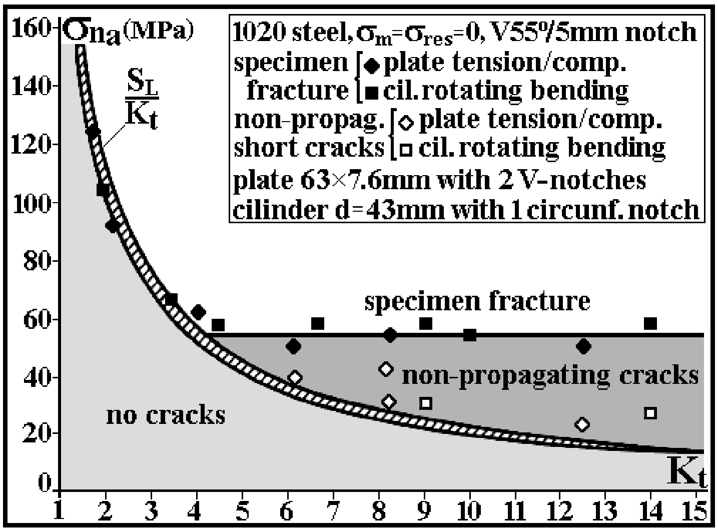

Figure 1. Classical data showing that non-propagating fatigue cracks are generated at the notch roots if $S_L/K_t < \sigma_n < S_L/K_f$.[2]

The gradients of the stress fields around notch roots affect the fatigue crack propagation (FCP) behavior of short cracks emanating from them. For any given material, q depends not only on the notch tip radius ρ, but also on its depth b, meaning that shallow and elongated notches of same ρ may have quite different q. Note that "short crack" here means "mechanical" not "microstructural" short crack, since material isotropy is assumed in their modeling, a simplified hypothesis corroborated by the tests. Short cracks must behave differently from long cracks, since their FCP threshold must be smaller than the long crack threshold $\Delta K_{th}(R)$, otherwise the stress range $\Delta\sigma$ required to propagate them would be higher than the material fatigue limit $\Delta S_L(R)$. Indeed, assuming that the FCP process is primarily controlled by the stress intensity factor (SIF) range, $\Delta K \propto \Delta\sigma\sqrt{(\pi a)}$, if short cracks with $a \to 0$ had the same $\Delta K_{th}(R)$ threshold of long cracks, their propagation by fatigue would require $\Delta\sigma \to \infty$, a physical non-sense.[4] The FCP threshold of short fatigue cracks under pulsating loads $\Delta K_{th}(a, R = 0)$ can be modeled using El Haddad-Topper-Smith (ETS) characteristic size a_0, which is estimated from $\Delta S_0 = \Delta S_L(R = 0)$ and $\Delta K_0 = \Delta K_{th}(R = 0)$.[5] This clever trick reproduces the Kitagawa-Takahashi[6] plot trend, using a modified SIF range $\Delta K'$ to describe the fatigue propagation of any crack, short or long.

$$\Delta K' = \Delta\sigma\sqrt{\pi(a+a_0)}\text{, where } a_0 = (1/\pi)(\Delta K_0/\Delta S_0)^2 \qquad (1)$$

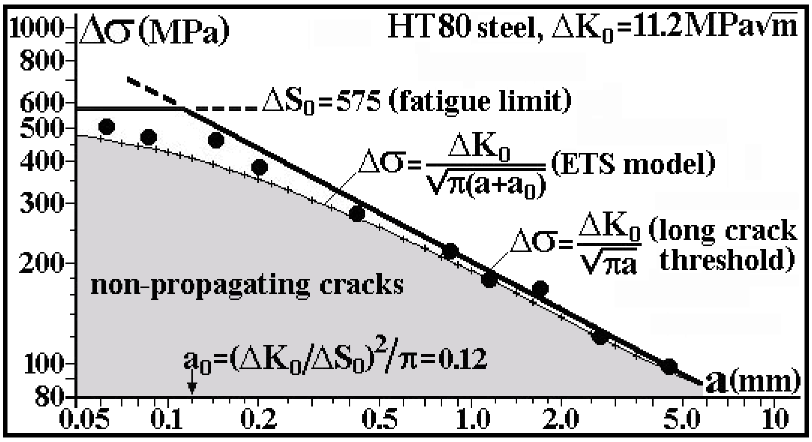

Figure 2. Kitagawa-Takahashi plot describing the fatigue propagation of short and long cracks under pulsating loads (R = 0) in a HT80 steel with ΔK_0 = 11.2 MPa√m and ΔS_0 = 575 MPa.

As ETS $\Delta K'$ has been deduced using the Griffith's plate SIF, $\Delta K = \Delta\sigma\sqrt{(\pi a)}$,[7] it is important to use the non-dimensional geometry factor $g(a/w)$ of the general SIF expression $\Delta K = \Delta\sigma\sqrt{(\pi a)}\cdot g(a/w)$ to deal with other geometries, re-defining:

$$\Delta K' = g(a/w)\cdot\Delta\sigma\sqrt{\pi(a+a_0)}\text{, where } a_0 = (1/\pi)\left[\Delta K_0/(g(a/w)\cdot\Delta S_0)\right]^2 \qquad (2)$$

But the tolerable stress range $\Delta\sigma$ under pulsating loads tends to the fatigue limit ΔS_0 when $a \to 0$ only if $\Delta\sigma$ is the notch root (instead of the nominal) stress range. However, $g(a/w)$ found in SIF tables usually include the notch SCF, thus they use $\Delta\sigma$ instead of $\Delta\sigma_n$ as the nominal stress. A clearer way to define a_0 when the short crack departs from a notch root is to explicitly recognize this practice, separating the geometry factor $g(a/w)$ into two parts: $g(a/w) = \eta\cdot\varphi(a)$, where $\varphi(a)$ describes the stress gradient ahead of the notch tip, which tends to the SCF as the crack length $a \to 0$, whereas η encompasses all the remaining terms, such as the free surface correction (Equation 3).

$$\Delta K' = \eta\cdot\varphi(a)\cdot\Delta\sigma\sqrt{\pi(a+a_0)}\text{, where } a_0 = (1/\pi)\left[\Delta K_0/(\eta\cdot\Delta S_0)\right]^2 \qquad (3)$$

Operationally, the short crack problem can be better and easier treated by letting the SIF range ΔK retain its original equation, while the FCP threshold expression (under pulsating loads) is modified to become a function of the crack length a, namely $\Delta K_0(a)$, resulting in Equation 4.

$$\Delta K_0(a) = \Delta K_0\cdot\sqrt{a/(a+a_0)} \qquad (4)$$

The ETS equation can be seen as one possible asymptotic match between the short and long crack behaviors. Following Bazant's[8] reasoning, a more general equation can be used introducing an adjustable parameter γ to fit experimental data.

$$\Delta K_0(a) = \Delta K_0\cdot\left[1+(a_0/a)^{\gamma/2}\right]^{-1/\gamma} \qquad (5)$$

ISSN 1516-392X

Equations 1 to 4 result from Equation 5 if $\gamma = 2$. The bi-linear limit, $\Delta\sigma(a \leq a_0) = \Delta S_0$ for short cracks, and $\Delta K_0(a \geq a_0) = \Delta K_0$ for long ones, is obtained when $g(a/w) = \eta \cdot \varphi(a) = 1$ and $\gamma \to \infty$. Most short crack FCP data is fitted by $\Delta K_0(a)$ curves with $1.5 \leq \gamma \leq 8$, but $\gamma = 6$ better reproduces classical q-plots based on data measured by testing semi-circular notched fatigue TS.(2,3) Using Equation 5 as the FCP threshold, then any crack departing from a notch under pulsating loads should propagate if:

$$\Delta K = \eta \cdot \varphi(a/\rho) \cdot \Delta\sigma\sqrt{\pi a} > \Delta K_0(a) = \Delta K_0 \cdot \left[1 + (a_0/a)^{\gamma/2}\right]^{-1/\gamma} \quad (6)$$

Where $\eta = 1.12$ is the free surface correction. As fatigue depends on two driving forces, $\Delta\sigma$ and σ_{max}, Equation 6 can be extended to consider σ_{max} (indirectly modeled by the R-ratio) influence in short crack behavior. First, the short crack characteristic size should be defined using the FCP threshold for long cracks $\Delta K_R = \Delta K_{th}(a >> a_R, R)$, and the fatigue limit ΔS_R, both measured or properly estimated at the desired R-ratio.

$$a_R = (1/\pi)\left[\Delta K_R/(1.12 \cdot \Delta S_R)\right]^2 \quad (7)$$

Likewise, the corresponding short crack FCP threshold should be re-written as Equation 8.

$$\Delta K_R(a) = \Delta K_R \cdot \left[1 + (a_R/a)^{\gamma/2}\right]^{-1/\gamma} \quad (8)$$

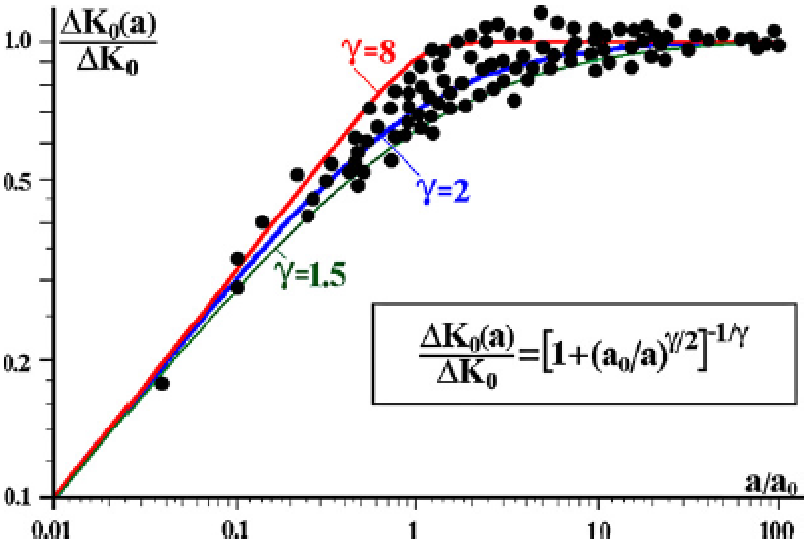

Figure 3. Ratio between short and long crack propagation thresholds as a function of a/a_0.

2 BEHAVIOR OF SHORT CRACKS DEPARTING FROM SLENDER NOTCHES

Before jumping into more elaborated mechanics, it is well worth to justify using relatively simple arguments why small cracks that depart from notch roots can propagate for a while before stopping and becoming non-propagating under fixed loading conditions. This fact may appear at first sight to be a paradox, since cracks are sharper than notches. In fact, it is not unreasonable to think that if a given fatigue load can start a crack from a notch, then it should be able to continue to propagate it. But the cracks behavior is more interesting than that. Indeed, let's start estimating the SIF of a small crack of size a that departs from the (elliptical) notch tip of an Inglis

ISSN 1516-392X

plate loaded in mode I, with semi-axes $b >> a$ and c, and root radius $\rho = c^2/b$. The $2b$ axis is centered at the x co-ordinate origin, σ_n is the nominal stress perpendicular to a and b. In this case, $K_I(a) \cong \sigma_n \cdot \sqrt{(\pi a)} \cdot f_1(a, b, c) \cdot f_2(free\ surface)$, where $f_1(a, b, c) \cong \sigma_y(x)/\sigma_n$; $\sigma_y(x)$ is the σ_y stress distribution at ($x = b + a$, $y = 0$) ahead of the notch tip when there is no crack; and $f_2 = 1.12$. The function $f_1(x = b + a, y = 0)$ is given by Schijve:[9]

$$f_1 = \frac{\sigma_y(x, y=0)}{\sigma_n} = 1 + \frac{(b^2 - 2bc)(x - \sqrt{x^2 - b^2 + c^2})(x^2 - b^2 + c^2) + bc^2(b - c)x}{(b-c)^2(x^2 - b^2 + c^2)\sqrt{x^2 - b^2 + c^2}} \tag{9}$$

The slender the elliptical notch is, meaning the smaller their semi-axes c/b and tip radius to depth ρ/b ratios are, the higher is its SCF. But high K_t imply in steeper stress gradients $\partial\sigma_y(x, y = 0)/\partial x$ around notch tips, since LE stress concentration induced by any elliptical hole drops from $K_t = 1 + 2b/c = 1 + 2\sqrt{(b/\rho)} = \sigma_y(1)/\sigma_n \geq 3$ at its tip border to $1.82 < K_{1.2} = \sigma_y(1.2)/\sigma_n < 2.11$ (for $b \geq c$) at a point just $b/5$ ahead of it, meaning their Saint Venant's controlling distance is associated with their depth b, not with their tip radii ρ.[1] This is the cause for the peculiar growth of short cracks which depart from elongated notch roots. Their SIF, which should tend to increase with their length $a = x - b$, may instead decrease after they grow for a short while because the SCF effect in $K_I \cong 1.12 \cdot \sigma_n \sqrt{(\pi a)} \cdot f_1$ may decrease sharply due the high stress drop close to the notch tip, overcompensating the crack growth effect. This $K_I(a)$ estimate can be used to evaluate non-propagating fatigue cracks tolerable at notch roots, using the short crack FCP behavior.
E.g., if a large steel plate with $S_U = 600\ MPa$, $S_L = 200\ MPa$ and $\Delta K_0 = 9\ MPa\sqrt{m}$ works under $\Delta\sigma_n = 100\ MPa$ at $R = -1$, verify if it is possible to change a circular $d = 20\ mm$ central hole by an elliptical one with $2b = 20\ mm$ (perpendicular to σ_n) and $2c = 2\ mm$, without inducing the plate to fail by fatigue. Neglecting the buckling problem, important in thin plates, this large circular hole has a safety factor against fatigue crack initiation $\phi_F = S_L/K_f \cdot \sigma_n = 200/150 \cong 1.33$, as it has $K_f \cong K_t = 3$. But the sharp elliptical hole would not be admissible by traditional SN routines, since it has $\rho = c^2/b = 0.1\ mm$, thus a very high $K_t = 1 + 2b/c = 21$. Its notch sensitivity estimated from the usual Peterson q plot[10] would be $q \cong 0.32 \Rightarrow K_f = 1 + q \cdot (K_t - 1) = 7.33$, thus it would induce $K_f \cdot \sigma_n = 376\ MPa > S_L$.
However, as this K_f value is considerably higher than typical values reported in the literature,[1,10,12] it is worth to re-study this problem considering the short crack FCP behavior. Supposing $\Delta K_{th}(R < 0) \cong \Delta K_0$ as usual, $\Delta K_0(a) = \Delta K_0/[1+(a_0/a)]^{-0.5}$ (by ETS), $S_L' = 0.5 S_U$ (the material fatigue limit, as FCP modeling does not need modifying factors required to estimate S_L), estimating by Goodman $\Delta S_0 = S_U/1.5 = 2S_L'/1.5$, and using $a_0 = (1/\pi)(1.5\Delta K_0/1.12 \cdot S_U)^2 \cong 0.13\ mm$, the SIF ranges $\Delta K_I(a)$ for the two holes are compared to the FCP threshold $\Delta K_0(a)$ in Figure 4. The SIF for cracks departing from the circular notch remains below the $\Delta K_0(a)$ FCP threshold curve (which considers the short crack behavior) up to $a \cong 1.54\ mm$. Thus, if a small surface scratch locally augments the stress range and initiates a tiny crack at that hole border, it would not propagate under this fixed $\Delta\sigma_n = 100\ MPa$ and $R = -1$ load, confirming its "safe" prediction made by traditional SN procedures. Only if a crack with $a > 1.54\ mm$ is introduced at this hole border by any other means, it would propagate by fatigue under those otherwise safe loading conditions.

Under these same loading conditions, the $\Delta K_I(a)$ curve for the elliptical hole starts above $\Delta K_0(a)$, thus a crack should initiate at its border, as expected from its high K_t. But as this tiny crack propagates through the high stress gradient ahead of the notch root, it sees rapidly diminishing stresses around its tip during its early growth, which overcompensate the increasing crack size effect on $\Delta K_I(a)$. This crack SIF becomes smaller than $\Delta K_0(a)$ at $a \cong 0.33\ mm$, when it stops and becomes non-propagating (if $\Delta\sigma_n$ and R remain fixed) (Figure 4).

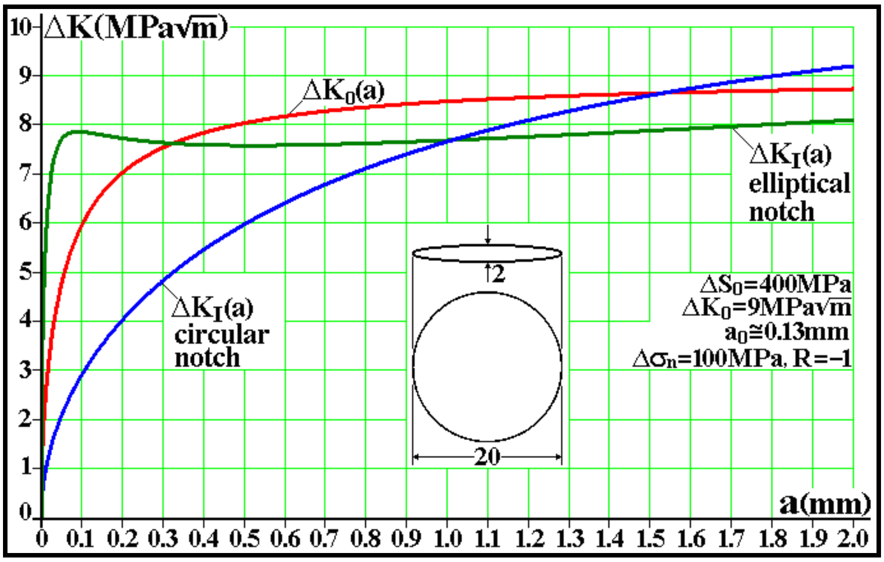

Figure 4. By Equation 9, cracks should not initiate at the circular hole border, which tolerates cracks $a < 1.54\ mm$, while the crack which initiates at the elliptical notch tip stops after reaching $a \cong 0.33\ mm$.

As fatigue failures include not only the crack initiation phase, but also its growth up to fracture, both notches could be considered safe for this service loading conditions ($\Delta\sigma_n = 100\ MPa$ and $R = -1$). But the non-propagating crack at the elliptical notch tip, a clear evidence of fatigue damage, renders it much less robust than the circular one, as discussed in Castro e Meggiolaro.(1) For analysis purposes, the SIF range of a single crack with length a emanating from a semi-elliptical notch with semi-axes b and c (where b is in the same direction as a) at the edge of a very large plate loaded in mode I can be written as Equation 10.

$$\Delta K_I = \eta \cdot F(a/b, c/b) \cdot \Delta\sigma\sqrt{\pi a} \qquad (10)$$

Where η = 1.12, and $F(a/b, c/b)$ can be expressed as a function of the dimensionless parameter $s = a/(b + a)$ and of the notch SCF (Equation 11).

$$K_t = [1 + 2(b/c)] \cdot \left\{1 + \left[0.12/(1 + c/b)^{2.5}\right]\right\} \qquad (11)$$

To obtain expressions for F, extensive finite element calculations were performed for several cracked semi-elliptical notches. The numerical results, which agreed well with standard solutions (11), were fitted within 3% using empirical Equations 2 and 3.

$$F(a/b, c/b) \equiv f(K_t, s) = K_t\sqrt{\left[1 - exp\left(-sK_t^2\right)\right]/sK_t^2}\ , \ c \le b \text{ and } s = a/(b + a) \qquad (12)$$

$$F'(a/b, c/b) \equiv f'(K_t, s) = K_t\left[1 - exp\left(-K_t^2\right)\right]^{-s/2}\sqrt{\left[1 - exp\left(-sK_t^2\right)\right]/sK_t^2}\ , \ c \ge b \qquad (13)$$

The SIF expressions include the semi-elliptical notch effect through F or F'. Indeed, as $s \to 0$ when $a \to 0$, the maximum stress at its tip $\sigma_{max} \to F(0, c/b)\cdot\sigma_n = K_t\cdot\sigma_n$. Thus, the η-factor, but not the $F(a/b,c/b)$ part of K_I, should be considered in the short surface crack characteristic size a_0 (Equation 3).
Note that the semi-elliptical K_t includes a term $[1 + 0.12/(1 + c/b)^{2.5}]$ which could be interpreted as the notch free surface correction (FSC). Thus, as $c/b \to 0$ and the semi-elliptical notch tends to a crack, its $K_t \to 1.12\cdot 2\sqrt{(b/\rho)}$. Such 1.12 factor is the notch FSC, not the crack FSC η. Indeed, when $c/b \to 0$, this 1.12 factor disappears from the F expression: $F(a/b, 0) = 1/\sqrt{s} \Rightarrow \Delta K_I = \eta\cdot F\cdot\Delta\sigma\cdot[\pi\cdot a]^{0.5} = \eta\cdot\Delta\sigma\cdot[\pi\cdot(a + b)]^{0.5}$, as expected, since the resulting crack for $c \to 0$ would have length $a + b$.
Traditional q estimates, based on the fitting of questionable semi-empirical equations to few experimental data points, assume it depends only on the notch root ρ and on the material ultimate strength S_U. Thus, similar materials with the same S_U but different ΔK_0 should have identical notch sensitivities. The same should occur with shallow and elongated notches of identical tip radii. However, whereas well established empirical relations relate the fatigue limit ΔS_0 to the tensile strength S_U of many materials, there are no such relations between their FCP threshold ΔK_0 and S_U. Moreover, it is also important to point out that the q estimation for elongated notches by the traditional procedures can generate unrealistic K_f values, as exemplified above.
In conclusion, such traditional estimates should not be taken for granted. The proposed model, on the other hand, is based on the FCP mechanics of short cracks which depart from elliptical notch roots, recognizing that their q values are associated with their tolerance to non-propagating cracks. It shows that their notch sensitivities, besides depending on ρ, ΔS_0, ΔK_0 and γ, are also strongly dependent on their shape, given by their c/b ratio.[2,3] Therefore, the proposed predictions indicate that these traditional notch sensitivity estimates should ***not*** be used for elongated notches, a forecast experimentally verified, as discussed in the following section.

3 AN ACCEPTANCE CRITERION FOR SHORT CRACKS

Based on the encouraging life estimations for fatigue crack re-initiation data,[1-3] the reverse path can be followed, assuming the methodology presented here can be used to generate an unambiguous acceptance criterion for small cracks, a potentially much useful tool for practical applications. Most structural components are designed against fatigue crack initiation, using εN or SN procedures which do not recognize cracks. Hence, their "infinite life" predictions may become unreliable when such cracks are introduced by any means, say by manufacturing or assembling problems, and not quickly detected and properly removed. Large cracks may be easily detected and dealt with, but small cracks may pass unnoticed even in careful inspections. In fact, if they are smaller than the guaranteed detection threshold of the inspection method used to identify them, they simply cannot be detected.
Thus, structural components designed for very long fatigue lives should be designed to be tolerant to such short cracks. However, this self-evident requirement is still not usually included in fatigue design routines, as most long-life designs just intend to maintain the stress range at critical points below their fatigue limits, guaranteeing that $\Delta\sigma < S_R/\phi_F$, where ϕ_F is a suitable safety factor. Nevertheless, most long-life designs work well, which means that they are somehow tolerant to undetectable or to functionally admissible short cracks. But the question "how much tolerant" cannot be

answered by *SN* or εN procedures alone. Such problem can be avoided by adding Equations 6 and 7 to the “infinite” life design criterion which, to tolerate a crack of size *a* in its simplest version, should be written as Equation 14.

$$\Delta\sigma < \Delta K_R \Big/ \left\{ \sqrt{\pi a} \cdot g(a/w) \cdot \left[1 + (a_R/a)^{\gamma/2}\right]^{1/\gamma} \right\}, \quad a_R = (1/\pi) \cdot [\Delta K_R / \eta \Delta S_R]^2 \qquad (14)$$

This criterion is applied elsewhere to evaluate a rare but quite interesting manufacturing problem: a batch of an important component was marketed with small surface cracks, causing some unexpected annoying field failures.(13)
Note that this model only describes the behavior of macroscopically short cracks, as it uses macroscopic material properties. Thus it can only be applied to short cracks which are large in relation to the characteristic size of the intrinsic material anisotropy (e.g. its grain size). Smaller cracks grow inside an anisotropic and usually inhomogeneous scale, thus their FCP is also affected by microstructural barriers, such as second phase particles or grain boundaries. However, as grains cannot be mapped in most practical applications, such problems, in spite of their academic interest, are not really a major problem from the fatigue design point of view.

4 A SHORT CRACK ACCEPTANCE CRITERION FOR EAC

The behavior of steels on sour environment is an important problem for the oil industry because oil and gas fields can contain considerably amounts of H_2S, and the costs for special alloys keeps increasing. But environmentally assisted cracking problems have been treated so far by integrity assessment procedures based on a policy of avoiding any problems by keeping the applied stress $\sigma < \sigma_{EAC}$ for non-cracked components, or their associated SIF $K < K_{IEAC}$ when flaws already exists. However, such criteria can be too conservative, since if there is any EAC sensitivity for a given material-environment pair, the material is summarily disqualified without considering stress analysis issues, possibly causing severe cost penalties. On the mechanical design stage, structural integrity assessments should be used to define a maximum tolerable flaw size, although EAC conditions may still be a little bit difficult to define due to the number of metallurgical and chemical variables which are traditionally treated as if they were decoupled from the stress field associated to them.
But we already know how different the behavior of deep and shallow fatigue cracks is, and how it can be treated in structural design. The aim of this work is to propose a possible extension of the proved criteria for accepting shallow fatigue cracks to the environmentally assisted cracking problem. If cracks behave well under EAC conditions, then a Kitagawa-like diagram can be used to quantify tolerable stresses, using the material EAC resistances to define a *short crack characteristic size* by Equation 15.

$$a_0 = (1/\pi) \cdot (K_{IEAC} / \eta \cdot S_{EAC})^2 \qquad (15)$$

Where K_{IEAC} is the resistance to crack propagation and S_{EAC} is the resistance to crack initiation under fixed stress conditions in the material-environment pair. This model assumes that the mechanical parameters that govern the environmentally assisted cracking problem behave analogously to the equivalent parameters $\Delta K_{th}(R)$ and $\Delta S_L(R)$ that control the fatigue problem (Figure 5).
If cracks loaded under EAC conditions behave mechanically as they should, meaning if their driving force is indeed the stress intensity factor applied on them; and if the

ISSN 1516-392X

chemical effects that influence their behavior are completely described by the material resistance to crack initiation from smooth surfaces quantified by S_{EAC}, and by its resistance to crack propagation measured by K_{IEAC}; then it can be expected that EAC cracks may depart from sharp notches and then stop, due to the stress gradient ahead of the notch tips, eventually becoming non-propagating cracks, as it occurs in the fatigue case. Consequently, if the size of non-propagating short cracks can be calculated using the same procedures useful for fatigue case, then the resistance to that kind of defect can be properly quantified using an EAC notch sensitivity factor in structural integrity assessments. Therefore, a design criterion to avoid EAC problems could be proposed as Equation 16.

$$a_{max} \leq (1/\pi)\cdot\left(K_{IEAC}\,(1+a_0/a)^{\gamma/2} \Big/ \sqrt{\pi a}\cdot g(a/w)\right)^{-1/\gamma} \qquad (16)$$

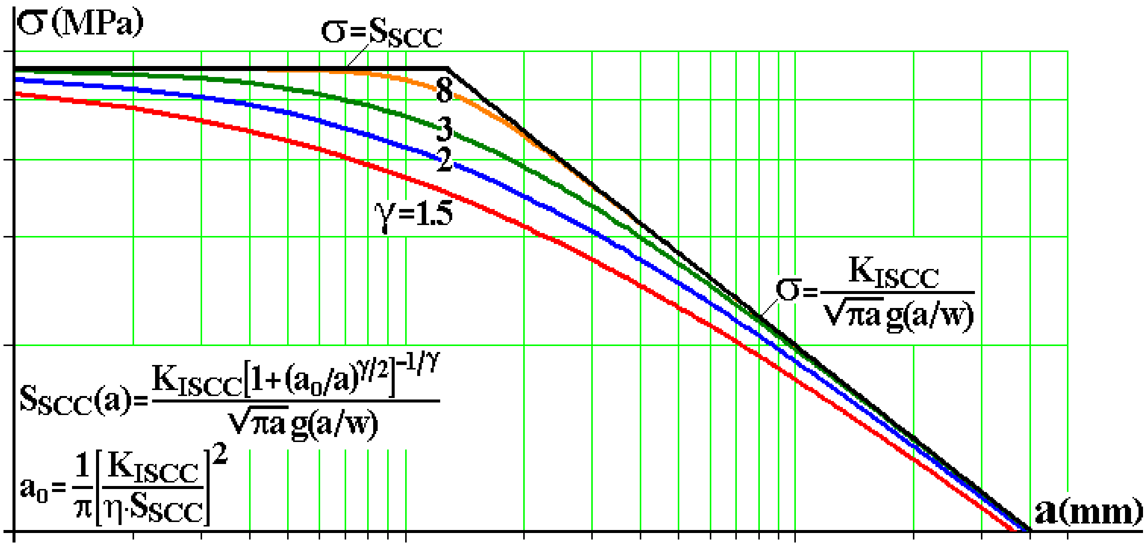

Figura 5: A Kitagawa-Takahashi-like plot proposed to describe the environmentally assisted cracking behavior of short and deep flaws for structural design purposes.

5 EDUCATED GUESSES ON TOLERABLE CRACKS UNDER EAC CONDITIONS

It is now possible to estimate a characteristic (a_0) and tolerable (a_{max}) sizes for a few cracks that initiate from notches with depth b = 10 mm and tip radius ρ using S_{EAC} and K_{IEAC} data gathered on the literature[13-16] for 3 material-environment pairs.

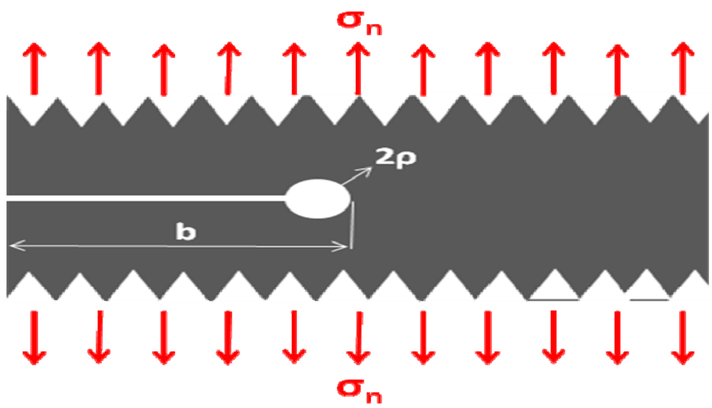

Figure 6. Notches parameters for non-propagating cracks.

ISSN 1516-392X

Table 1. Estimated results for tolerable crack sizes at some notch geometries

Material / Environment	Aluminum 2024 / Gallium	Aluminum 2024 / NACE Solution	API 5L X-80 steel / NACE Solution
S_{EAC} (MPa)	70	140	440
K_{IEAC} (MPa*√m)	1.2	8	30
a_0 (mm)	0.075	0.829	1.18
b (mm)	10	10	10
ρ (mm)	0.335	3.136	4.9
K_t	12.881	4.754	3.982
$\sigma = S_{EAC} / K_t$ (MPa)	5.434	29.448	110.5
a_{max} (mm)	1.9	6.65	5.41

The motivation to use the three material-environment pairs on Table 1 is simple: It is a little bit hard to find the parameters K_{IEAC} and S_{EAC} together on the literature. Maybe this could be explained by the lack of models that try to unify these parameters as driving forces acting together.

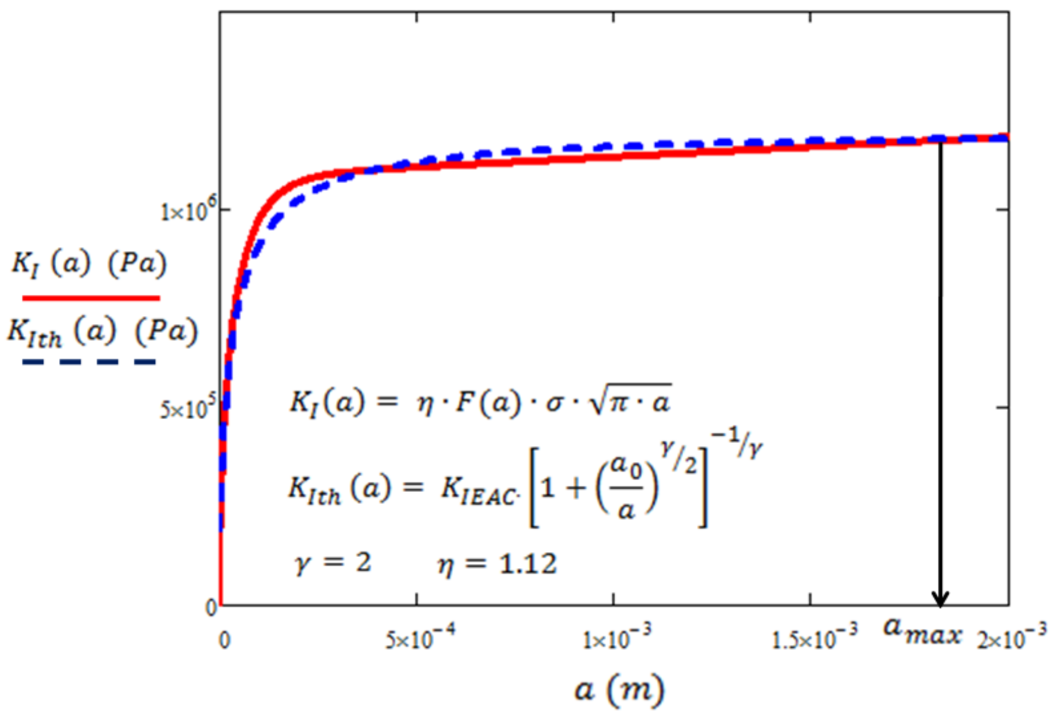

Figure 7. Environmental assisted cracking criteria plot for Aluminum 2024 under Gallium Exposure.

Figure 7 shows a graphical interpretation for the proposed model equations. The maximum allowed crack size is obtained when the Stress Intensity Factor $K_I(a)$ becomes higher than the Stress Intensity Threshold $K_{Ith}(a)$.

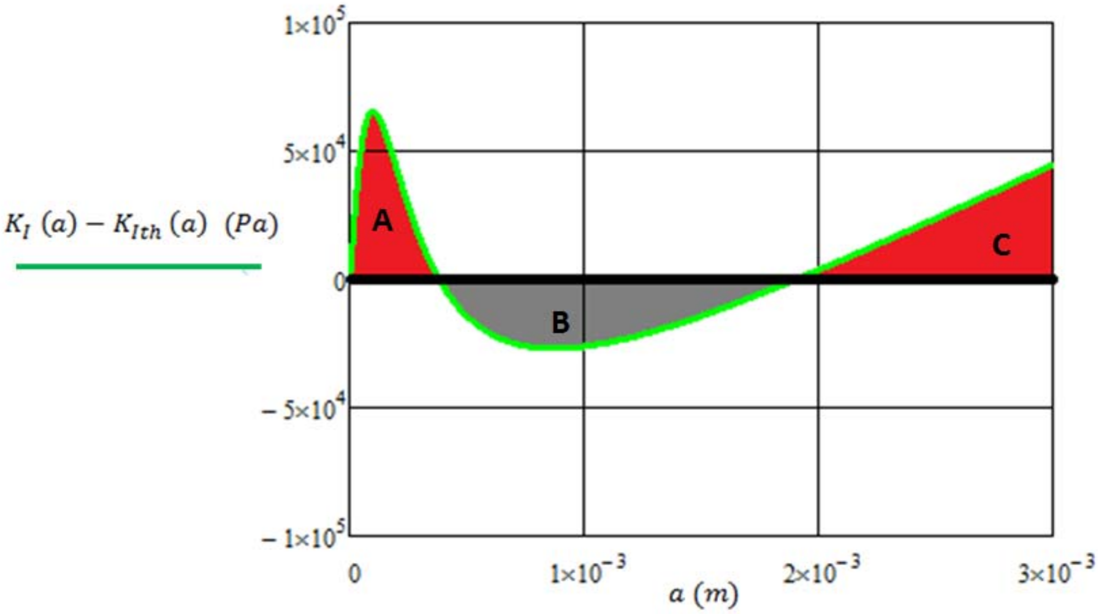

Figure 8. Criteria plot of propagating cracks for Aluminum 2024 under Gallium Exposure.

Graphical solutions can provide other important information as illustrated in figure 8, which shows that a flaw on the size region "A" could propagate until reaching the region "B" when it becomes non-propagating because K_{Ith} (a) > K_I (a). Nevertheless all flaws sizes on the region "C" are considered non acceptable cracks, since the difference $K_I(a) – K_{Ith}(a)$ becomes again positive after leaving the safe region B.

6 CONCLUSIONS

A generalized El Haddad-Topper-Smith's parameter was used to model the threshold stress intensity range for short cracks dependence on the crack size, as well as the behavior of non-propagating environmentally assisted cracks. This dependence was used to estimate the notch sensitivity factor *q* of elongated notches, from studying the propagation behavior of short non-propagating cracks that may initiate from their tips. It was found that the notch sensitivity of elongated slits has a very strong dependence on the notch aspect ratio, defined by the ratio *c/b* of the semi-elliptical notch that approximates the slit shape having the same tip radius. These predictions were calculated by numerical routines. Based on this promising performance, a criterion to evaluate the influence of small or large surface flaws in the environmental assisted cracking was proposed.

Such estimates are encouraging results that deserve to be properly studied trough a serious experimental program, because they can be associated with potentially non-negligible economic savings. However, it is important to emphasize that at this stage the most that can surely stated is that numerical speculations based on sound mechanical arguments indicate that environmental assisted cracking phenomena may be treated by fracture mechanic tools for design purposes.

Acknowledgements

CNPq and Petrobras have provided research scholarships for the authors. Dr. A. Vasudevan from the Office of Naval Research, US Navy, has contributed with many important suggestions.

ISSN 1516-392X

REFERENCES

1 CASTRO, J.T.P.; MEGGIOLARO, M.A. Fatigue – Techniques and Practices for Structural Dimensioning under Real Service Loads (in Portuguese), ISBN 978-1449514709. CreateSpace; 2009
2 MEGGIOLARO, M.A.; MIRANDA, A.C.O.; CASTRO, J.T.P. "Short crack threshold estimates to predict notch sensitivity factors in fatigue", Int J Fatigue v.29, p.2022–2031, 2007
3 WU, H.; IMAD, A.; NOUREDDINE, B.; CASTRO, J.T.P.; MEGGIOLARO, M.A.; MIRANDA, A.C.O. On the prediction of the residual fatigue life of cracked structures repaired by the stop-hole method. Int J Fatigue v.32, p.670-677, 2010.
4 LAWSON, L.; CHEN, E.Y.; MESHII, M. Near-threshold fatigue: a review. Int J Fatigue v.21, p.15-34, 1999.
5 EL HADDAD MH, TOPPER TH, SMITH KN. Prediction of non-propagating cracks. Engineering Fracture Mechanics v.11, p.573-584, 1979.
6 Kitagawa, H.; Takahashi, S. Applicability of fracture mechanics to very small crack or cracks in the early stage. Proceedings of the 2nd International Conference on Mechanical Behavior of Materials. ASM; 1976.
7 YU, M.T.; Duquesnay, D.L.; Topper, T.H. Notch fatigue behavior of 1045 steel. Int J Fatigue v.10, p.109-116, 1988.
8 BAZANT ZP. Scaling of quasibrittle fracture: asymptotic analysis. Int J Fracture v. 83, p.19-40, 1977.
9 SCHIJVE, J. Fatigue of Structures and Materials. Kluwer; 2001.
10 DOWLING, N.E. Mechanical Behavior of Materials. 3rd ed. Prentice Hall; 2007.
11 TADA. H.; PARIS, P.C.; IRWIN, G.R. The Stress Analysis of Cracks Handbook. Del Research; 1985.
12 CASTRO, J.T.P.; MEGGIOLARO, M.A.; MIRANDA, A.C.O.; WU, H.; IMAD, A.; NOUREDDINE, B. Prediction of fatigue crack initiation lives at elongated notch roots using short crack concepts", Int J Fatigue, DOI: 10.1016/j.ijfatigue.2011.10.010, in press.
13 HOLTAM, C. Structural integrity assessment of C-Mn pipeline exposed to sour environments. Dissertation Thesis of the degree Doctor of Engineering, Loughborough University; 2010.
14 DIETZEL, W. Fracture mechanics approach to stress corrosion cracking, Anales de Mecánica de la Fractura, Vol. 18, (2001).
15 ITOH, A.; IZUMI, J.; INA, K.; KOIZUMI,H. Brittle-to-ductile transition in polycrystalline aluminum containing gallium in the grain boundaries, 15th International Conference on the Strength of Materials (ICSMA-15), 2010.
16 KOLMAN, D.G., CHAVARRIA, R. Liquid Metal Embrittlement of 7075 Aluminum and 4340 Steel Compact Tension Specimens by Gallium. J. Test. Evaluation, Vol. 30 (N°5),2002.