ISSN 1516-392X

Theme: Fracture Mechanics and Structural Integrity

# TOLERANCE TO SHORT CRACKS IN FATIGUE AND ENVIRONMENTALLY ASSISTED CRACKING CONDITIONS*

*Marco Antonio Meggiolaro*[1]
*Jaime Tupiassú Pinho de Castro*[1]

## Abstract
Notches are preferential sites for fatigue and for environmentally assisted cracking (EAC) initiation. Semi-empirical notch sensitivity factors have been used for a long time to quantify notch effects on fatigue design. Recently, this concept has been mechanically modeled using techniques which properly consider the notch tip stress gradient influence on the fatigue behavior of mechanically short cracks. This model properly calculates such values from the basic fatigue resistances of the material, its fatigue limit and crack growth threshold, considering the characteristics of the notch geometry and of the loading, without the need for any adjustable parameter. Such criteria to estimate notch sensitivity and tolerable short cracks on fatigue have been extended to EAC conditions and verified by proper tests. In its simplest version, the criterion for the maximum tolerable stress under EAC conditions uses the resistances to crack initiation and to large crack propagation and the characteristic short crack size under EAC, considering the crack size and stress intensity factor. Moreover, the tolerance to short cracks under fatigue and under EAC conditions can be unified in an extended Kitagawa-Takahashi diagram, a new and potentially very useful tool for material selection tasks.
**Keywords:** Short cracks; Defect-tolerant criteria; Notch sensitivity in fatigue and EAC.

[1] *Ph.D., Professor of Mechanical Engineering, Pontifical Catholic University of Rio de Janeiro, Brazil.*

* *Technical contribution to the 69th ABM International Annual Congress and to the ENEMET, July 21st -25th, 2014, São Paulo, SP, Brazil.*

ISSN 1516-392X

## 1 INTRODUCTION

Fatigue damage depends on two driving forces, one that activates cyclic and the other that activates static damage mechanisms. So, fatigue crack growth (FCG) rates on any given environment depend on $\Delta K$ and $K_{max}$, the range and maximum of their stress intensity factors (SIF), or on any other pair of independent parameters related to them. In fact, even though $R$ is not a crack driving force, it is more usual to use $\Delta K$ and $R = K_{min}/K_{max}$ to model FCG problems. Such choice is operationally convenient because it is easier to compare with familiar concepts long used by engineers.
To propagate *long* cracks by fatigue under fixed $\{\Delta K, K_{max}\}$ or $\{\Delta K, R\}$ loading conditions, the applied SIF range $\Delta K$ must be higher than the FCG threshold at the given $R$-ratio, $\Delta K_{th}(R) = \Delta K_{thR}$. Cracks are *short* while their actual FCG thresholds are smaller than the long crack FCG threshold, thus while such cracks can grow under $\Delta K < \Delta K_{thR}$ (otherwise the stress ranges $\Delta\sigma$ needed to propagate short cracks at a given $R$ would be higher than their fatigue limits $\Delta S_L(R) = \Delta S_{LR}$, the stress range that initiates and propagates cracks in smooth specimens at that $R$-ratio.) Indeed, if at any given $R$-ratio the FCG process is driven by the SIF range $\Delta K \propto \Delta\sigma\sqrt{(\pi a)}$, and if very short cracks with size $a \to 0$ had the same $\Delta K_{thR}$ threshold the long cracks have, then they would need $\Delta\sigma \to \infty$ to grow by fatigue, a meaningless requirement. If the stresses are not induced by external loads only, i.e. if the cracks start from notch tips or from smooth surfaces also loaded by residual stress fields caused by plastic strain gradients or any other mechanism, such resident stresses must be added to the externally applied stresses as static loading components that affect $R$ but not $\Delta K$.
*Microstructurally* short cracks, small compared to the grain size *gr*, are much affected by microstructural barriers like grain boundaries, so cannot be well modeled for structural design purposes using macroscopic stress analysis techniques and isotropic properties. *Mechanically* short cracks, on the other hand, with sizes $a > gr$, may be modeled by Linear Elastic Fracture Mechanics (LEFM) concepts if the stress field that surrounds them is predominantly LE, and if the material can be treated as isotropic and homogeneous in such a scale [1-3]. As near-threshold FCG is always associated with small scale yielding conditions, to check if short cracks really may be modeled in such a way, the idea is to follow Irwin's steps by first assuming that such concepts are valid and then verifying if their predictions are validated by proper tests. Hence, in the sequence, LEFM techniques are used to develop a model for the FCG behavior of mechanically short cracks, in particular those that depart from notches. Then notch sensitivity predictions based on their behavior are extended to model notch sensitivity effects under environmentally assisted cracking conditions.

## 2 THE BEHAVIOR OF SHORT CRACKS IN FATIGUE

To reconcile the traditional (crack initiation) fatigue limit, $\Delta S_{L0} = 2S_L(R = 0)$, with the FCG threshold of long cracks under pulsating loads, $\Delta K_{th0} = \Delta K_{th}(R = 0)$, El Haddad et al. [4-5] added to the physical crack size a hypothetical *short crack characteristic size* $a_0$, to force the SIF of all cracks, short or long, to obey the correct FCG limits:

$$\Delta K_I = \Delta\sigma\sqrt{\pi(a+a_0)}\text{, where } a_0 = (1/\pi)(\Delta K_{th0}/\Delta S_{L0})^2 \qquad (1)$$

In this way, long cracks with $a >> a_0$ do not grow by fatigue (in Griffith's plates under pulsating loads) if $\Delta K_I = \Delta\sigma\sqrt{(\pi a)} < \Delta K_{th0}$, while very small cracks with $a \to 0$ do not

* *Technical contribution to the 69th ABM International Annual Congress and to the ENEMET, July 21st -25th, 2014, São Paulo, SP, Brazil.*

ISSN 1516-392X

grow if $\Delta\sigma < \Delta S_{L0}$, as $\Delta K_I = \Delta\sigma\sqrt{(\pi a_0)} < \Delta S_{L0}\sqrt{(\pi a_0)} = \Delta K_{th0}$ in this case. Moreover, this clever idea fits reasonably well typical $\Delta\sigma_j \times a_j$ data points in Kitagawa-Takahashi diagrams, where $\Delta\sigma_j$ is the stress range needed to propagate a fatigue crack with size $a_j$, see Figure 1 [1]. This figure also shows the fatigue limit $\Delta S_{L0}$ and the stress range $\Delta\sigma(a) = \Delta K_{th0}/\sqrt{(\pi a)}$ associated to the long crack threshold, which limit the region that may contain non-propagating cracks, as well as the El Haddad-Topper-Smith (ETS) curve, which predicts that cracks of any size should stop when

$$\Delta\sigma(a) \le \Delta K_{th0}/\sqrt{\pi(a+a_0)} \qquad (2)$$

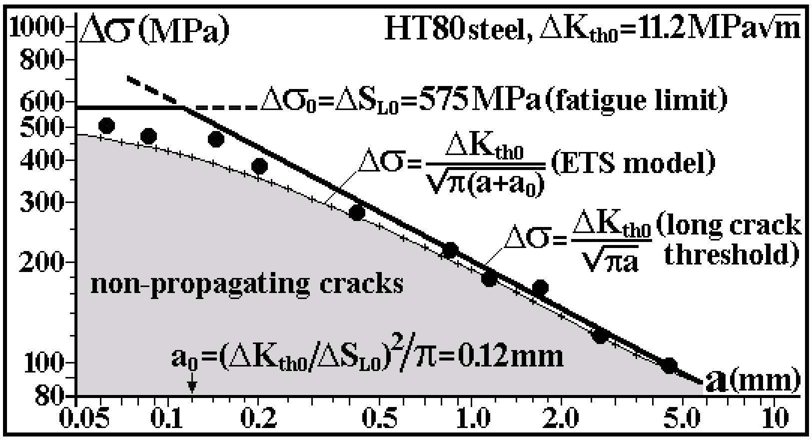


**Figure 1.** Stress ranges $\Delta\sigma(a)$ required to propagate cracks of size $a$ under $R = 0$ in an HT80 steel plate with $\Delta K_{th0} = 11.2MPa\sqrt{m}$ and $\Delta S_{L0} = 575MPa$: long cracks, with $a >> a_0$, stop when $\Delta\sigma \le \Delta K_{th0}/\sqrt{(\pi a)}$, while very short cracks, with $a \to 0$, stop when $\Delta\sigma \le \Delta S_{L0}$.

Steels typically have $6 < \Delta K_{th0} < 12MPa\sqrt{m}$, ultimate tensile strengths $400 < S_U < 2000MPa$, and fatigue limits $200 < S_L < 1000MPa$ (the best high-strength steels with very clean microstructures tend to maintain the trend $S_L \cong S_U/2$ for smooth test specimens). Consequently, the range of their fatigue limits under pulsating loads (those with $R = 0$) estimated by Goodman is

$$\Delta S_{L0} \cong 2S_U S_L/(S_U + S_L) \Rightarrow 260 < \Delta S_{L0} < 1300MPa \qquad (3)$$

Hence, the $a_0$ range in large steel plates with a central crack subject to pulsating tensile loads, estimated according to the ETS model is:

$$(1/\pi)\cdot(\Delta K_{th0min}/\Delta S_{L0max})^2 \cong 7 < a_0 < 700\mu m \cong (1/\pi)\cdot(\Delta K_{th0max}/\Delta S_{L0min})^2 \qquad (4)$$

Since such $a_0$ values are small, they justify the name "short crack characteristic size." Typical Al alloys ($30 < S_L < 230MPa$, $70 < S_U < 600MPa$, $40 < \Delta S_{L0} < 330MPa$, and $1.2 < \Delta K_{th0} < 5MPa\sqrt{m}$) have a little larger estimated $a_0$ range, $1\mu m < a_0 < 5mm$. So, it can be expected that short crack effects on materials with high $\Delta K_{th0}$ and low $\Delta S_{L0}$ to be more pronounced in Al alloys than in steels. Such values assume a through-thickness 1D crack, one that can be completely described by just one size parameter, but most small cracks probably should be better treated as 2D cracks as discussed latter on. Moreover, as the generic SIF of cracked structural components is $K_I = \sigma\sqrt{(\pi a)}\cdot g(a/w)$, Yu et al. [6] used the geometry factor $g(a/w)$ to generalize Equation (1), and redefined the short crack characteristic size by:

ISSN 1516-392X

$$\Delta K_I = \Delta\sigma\sqrt{\pi(a+a_0)}\cdot g(a/w)\text{, where } a_0 = (1/\pi)\cdot(\Delta K_{th0}/[\Delta S_{L0}\cdot g(a/w)])^2 \quad (5)$$

The largest stress range $\Delta\sigma$ that does not propagate microcracks in this case is also the fatigue limit, as it should: if $a << a_0$, $\Delta K_I = \Delta K_{th0} \Rightarrow \Delta\sigma \to \Delta S_{L0}$. However, when the crack starts from a notch, as usual, its driving force is the stress range at the notch tip, not the nominal stress range $\Delta\sigma_n$ normally used in SIF expressions. As in such cases the $g(a/w)$ factor includes the stress concentration effect of the notch $K_t$, it is better to split it into two parts: $g(a/w) = \eta\cdot\varphi(a)$, where $\varphi(a)$ quantifies the effect of the stress gradient near the notch tip, which tends towards $K_t$, i.e. $\varphi(a \to 0) \to K_t$, while the constant $\eta$ quantifies the effect of the other parameters that affect $K_I$, such as the free surface. So, it is better to redefine $a_0$ by:

$$\Delta K_I = \eta\cdot\varphi(a)\cdot\Delta\sigma_n\sqrt{\pi(a+a_0)}\text{, where } a_0 = (1/\pi)\cdot\left[\Delta K_{th0}/(\eta\cdot\Delta S_{L0})\right]^2 \quad (6)$$

As the stress ranges at notch tips must be smaller than the fatigue limit to avoid cracking, $\Delta\sigma(a \to 0) = K_t\Delta\sigma_n = \varphi(0)\Delta\sigma_n < \Delta S_{L0}$, the stress gradient quantified by $\varphi(a)$ does not affect $a_0$. However, since the SIFs are crack driving forces, they should be material-independent. Hence, the $a_0$ effect on the short crack behavior should modify FCG thresholds instead of SIFs, making them a function of the crack size, a trick that is quite convenient for operational reasons. In this way, the $a_0$-dependent FCG threshold for pulsating loads $\Delta K_{th}(a, R = 0) = \Delta K_{th0}(a)$ becomes

$$\frac{\Delta K_{th0}(a)}{\Delta K_{th0}} = \frac{\Delta\sigma\sqrt{\pi a}\cdot g(a/w)}{\Delta\sigma\sqrt{\pi(a+a_0)}\cdot g(a/w)} = \sqrt{\frac{a}{a+a_0}} \Rightarrow \Delta K_{th0}(a) = \Delta K_{th0}\left[1+(a_0/a)\right]^{-1/2} \quad (7)$$

Note that for $a >> a_0$ this short crack FCG threshold tends to $\Delta K_{th0}$, the long crack FCG threshold, and becomes independent of the crack size, as it should. Moreover, it may be convenient to assume that Eq. (7) is just one of the models that obey the long crack and short crack limit behaviors, introducing in the $\Delta K_0(a)$ definition an optional data fitting parameter $\gamma$ proposed by Bazant to obtain:

$$\Delta K_{th0}(a) = \Delta K_{th0}\left[1+(a_0/a)^{\gamma/2}\right]^{-1/\gamma} \quad (8)$$

This equation reproduces the ETS model when $\gamma = 2$, as well as the bi-linear limits $\Delta\sigma = \Delta S_{L0}$ and $\Delta\sigma = \Delta Kth_0/\sqrt{(\pi a)}$, when $\gamma \to \infty$. Most data on short cracks can be well fitted by $1.5 < \gamma < 8$ [1]. The curves shown in Fig. 2 illustrate the influence of $\gamma$ on the minimum stress ranges needed to propagate short or long cracks under pulsating loads as a function of the crack size $a$:

$$\Delta\sigma_0(a) = \left[\Delta K_{th0}/\sqrt{\pi a}\right]\cdot\left[(1+a/a_0)^{\gamma/2}\right]^{-1/\gamma} \quad (9)$$

However, as fatigue damage depends on two driving forces, $\Delta K$ and $K_{max}$, Equation (8) should be extended to consider the $\sigma_{max}$ influence (indirectly modeled by the $R$-ratio) on the short crack behavior. Thus, if $\Delta K_{thR} = \Delta K_{thR}(a >> a_R, R)$ is the FCG

---

ISSN 1516-392X

threshold for long cracks, $\Delta S_{LR} = \Delta S_L(R)$ is the fatigue limit at the desired $R$-ratio, and $a_R$ is the characteristic short crack size at that $R$, then:

$$\Delta K_{thR}(a) = \Delta K_{thR} \cdot \left[1+(a_R/a)^{\gamma/2}\right]^{-1/\gamma}, \text{ where } a_R = (1/\pi)\left[\Delta K_{thR}/(\eta \cdot \Delta S_{LR})\right]^2 \quad (10)$$

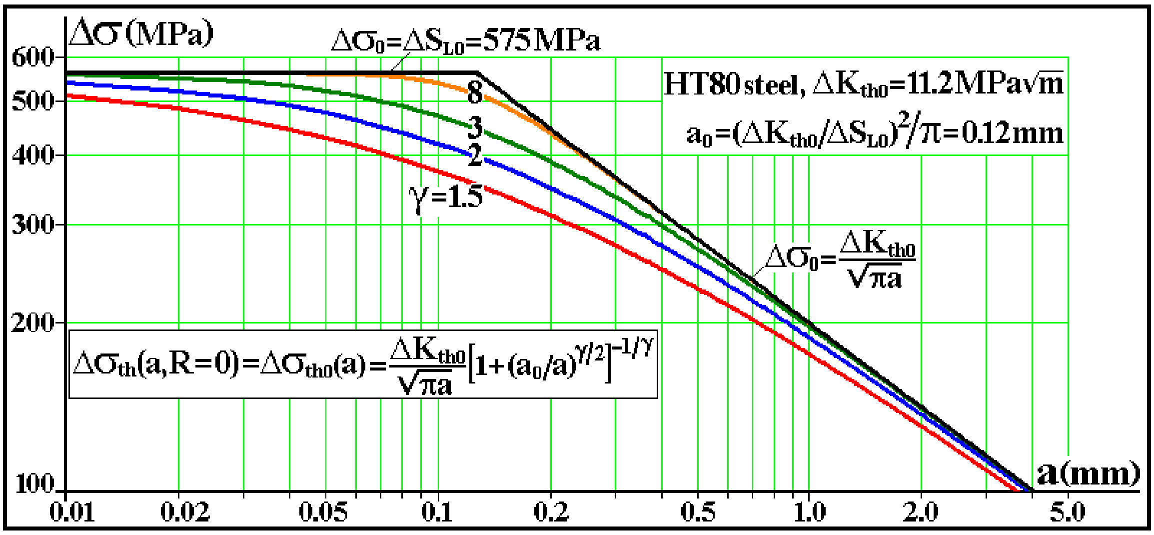


**Figure 2.** Influence of $\gamma$ in the fatigue limit curves $\Delta\sigma_0(a)$ predicted by Eq. (9): the larger $\gamma$ is, the faster $\Delta\sigma_0(a)$ tends to the bilinear limit defined by $\Delta\sigma_0 = \Delta K_{th0}/\sqrt{(\pi a)}$, the FCG threshold under pulsating loads for long cracks, and to $\Delta\sigma_0 = \Delta S_{L0}$, the fatigue limit under pulsating stresses for cracks with $a << a_0$.

Fatigue limits of notched components are estimated for structural design purposes using a fatigue stress concentration factor (SCF) $K_f = 1 + q \cdot (K_t - 1)$, where the notch sensitivity $q$ usually is still quantified by empirical curves fitted to just 7 experimental points compiled by Peterson a long time ago [7]. Such traditional $q$ values do not consider any crack effects. However, according to Frost [8], early data showing that small non-propagating fatigue cracks are found at notch tips when $\Delta S_L/K_t < \Delta\sigma_n < \Delta S_L/K_f$ goes back as far as 1949. So, it can be expected that $q$ can be predicted from the fatigue behavior of short cracks that emanate from notch tips, thus that such tiny cracks can be used to quantitatively explain why $K_f \leq K_t$. As shown in [9], this can be done using two dimensionless functions, $\varphi(a/\rho)$ related to the notch stress gradient, and $g(\Delta S_{L0}/\Delta\sigma, a/\rho, \Delta K_{th0}/\Delta S_{L0}\sqrt{\rho}, \gamma)$ which includes the effects of the applied stress range $\Delta\sigma$, the crack size $a$, the notch tip radius $\rho$, the fatigue resistances $\Delta S_{L0}$ and $\Delta K_{th0}$, and the data fitting exponent $\gamma$ (if it is used):

$$\varphi(a/\rho) > \frac{(\Delta S_{L0}/\Delta\sigma)\cdot\left[\Delta K_{th0}/(\Delta S_{L0}\sqrt{\rho})\right]}{\left\{(\eta\sqrt{\pi a/\rho})^{\gamma} + \left[\Delta K_{th0}/(\Delta S_{L0}\sqrt{\rho})\right]^{\gamma}\right\}^{1/\gamma}} \equiv g\left(\frac{\Delta S_{L0}}{\Delta\sigma}, \frac{a}{\rho}, \frac{\Delta K_{th0}}{\Delta S_{L0}\sqrt{\rho}}, \gamma\right) \quad (11)$$

If for a given $\gamma$ the system $\{\varphi/g = 1, \partial(\varphi/g)\partial x = 0\}$ is solved for several notch tip radii $\rho$ using $\kappa \equiv \Delta K_{th0}/\Delta S_{L0}\sqrt{\rho}$, then the notch sensitivity factor $q$ is obtained by:

$$q(\kappa,\gamma) \equiv [K_f(\kappa,\gamma) - 1]/(K_t - 1) \quad (12)$$

As structural components always contain tiny defects, when their size is not much smaller than $a_0$, their structural effects can thus be estimated assuming they behave

---

** Technical contribution to the 69th ABM International Annual Congress and to the ENEMET, July 21st -25th, 2014, São Paulo, SP, Brazil.*

ISSN 1516-392X

as mechanically short cracks using LEFM concepts, as detailed in the following sections.

## 3 INFLUENCE OF SHORT CRACKS ON THE FATIGUE LIMIT OF STRUCTURAL COMPONENTS

*SN* and $\varepsilon N$ methods are traditionally used to analyze and design supposedly crack-free components, but as it is impossible to guarantee that they are really free of cracks smaller than the detection threshold of the non-destructive inspection (NDI) methods used to check them, their predictions may become unreliable when such tiny defects are introduced by any means during manufacture or service. Therefore, structural components should be designed to tolerate undetectable short cracks.

Despite self-evident, this prudent requirement is still not included in most fatigue design routines, which just intend to maintain the service stresses at critical points below their fatigue limits, $\Delta\sigma < \Delta S_{LR}/\varphi_F$, where $\varphi_F$ is a suitable safety factor. Nevertheless, most long-life designs work just fine, hence they are somehow tolerant to undetectable or to functionally admissible short cracks. However, the question "how much tolerant" cannot be answered by *SN* or $\varepsilon N$ procedures alone. Such problem can be avoided by adding a tolerance to short crack requirement to their "infinite" life design criteria which, in its simplest version, may be given by

$$\Delta\sigma \le \Delta K_{thR} \Big/ \left\{\varphi_F \cdot \sqrt{\pi a}\cdot g(a/w)\cdot\left[1+(a_R/a)^{\gamma/2}\right]^{1/\gamma}\right\}, \quad a_R = (1/\pi)\left[\Delta K_{thR}/(\eta\Delta S_{LR})\right]^2 \qquad (13)$$

Since the fatigue limit $\Delta S_{LR}$ reflects the effect of microstructural defects inherent to the material, Eq. (13) complements it by quantifying the tolerance to cracks of size *a* (small or not) that may pass unnoticed in actual service conditions. The practical usefulness of this sensible criterion is illustrated by the following case study.

Due to a rare manufacturing problem, a batch of an important component was delivered with tiny elongated surface cracks (only detectable by a microscope), causing some unexpected and fazing failures. Estimate the effect of such small cracks in their fatigue strength, knowing that they have a *2* by *3.4mm* rectangular cross-section, are made from steel with $S_U = 990MPa$ and (uncracked) fatigue limit $S_L = 246MPa$, *and that* its fatigue limit at $R > -1$ can be estimated by Goodman as $S_L(R) = S_{LR} = S_L S_U(1 - R)/[S_U(1 - R) + S_L(1 + R)]$.

The FCG threshold is also needed to model short crack effects. If data is not available, as in this case, it can be estimated by $\Delta K_{th}(R \le 0.17) \cong \Delta K_{th0} = 6MPa\sqrt{m}$ and $\Delta K_{thR}(R > 0.17) = 7\cdot(1 - 0.85R)$ [10]. This risky practice increases the predictions uncertainty, but it is the only option available and assumes that $\Delta K_{thR}(R < 0) \cong \Delta K_{th0}$, a safe estimate (unless the load history contains severe compressive underloads that may accelerate the crack, not the case here.) Using the SIF of an edge cracked strip of width *w* loaded in mode I, the tolerable stress ranges under pulsating axial loads shown in Figure 3 can be estimated within a fatigue safety factor $\varphi_F$ by [11]:

$$\Delta\sigma_0 \le \frac{\Delta K_{th0}\big/\left(\varphi_F\sqrt{\pi a}\right)}{\sec\frac{\pi a}{2w}\sqrt{\frac{2w}{\pi a}\tan\frac{\pi a}{2w}}\left[0.752+2.02\frac{a}{w}+0.37\left(1-\sin\frac{\pi a}{2w}\right)^3\right]\left[1+\left(\frac{a_0}{a}\right)^{\gamma/2}\right]^{1/\gamma}} \qquad (14)$$

* *Technical contribution to the 69th ABM International Annual Congress and to the ENEMET, July 21st -25th, 2014, São Paulo, SP, Brazil.*

Such estimates can evaluate the effect of an accidental damage on the surface of otherwise well-behaved components, but they have limitations. They assume that the short crack grows unidimensionally (1D), but as they usually are small compared to the structural component dimensions, they are better described as 2D cracks that grow in two directions changing their shape at every load cycle, albeit maintaining their original plane under Mode I loads. Moreover, such estimates are valid for mechanical but not for microstructural short cracks, i.e. they are valid only for cracks with both *a* and $a_0$ larger than the grain size *gr*. The FCG behavior of microcracks with size $a < gr$ is sensitive to microstructural features such as the grain orientation, thus they cannot be properly modeled using macroscopic material properties. Such problems have academic interest [12], but as grains still cannot be mapped in practice, they cannot be properly used for structural engineering applications yet.

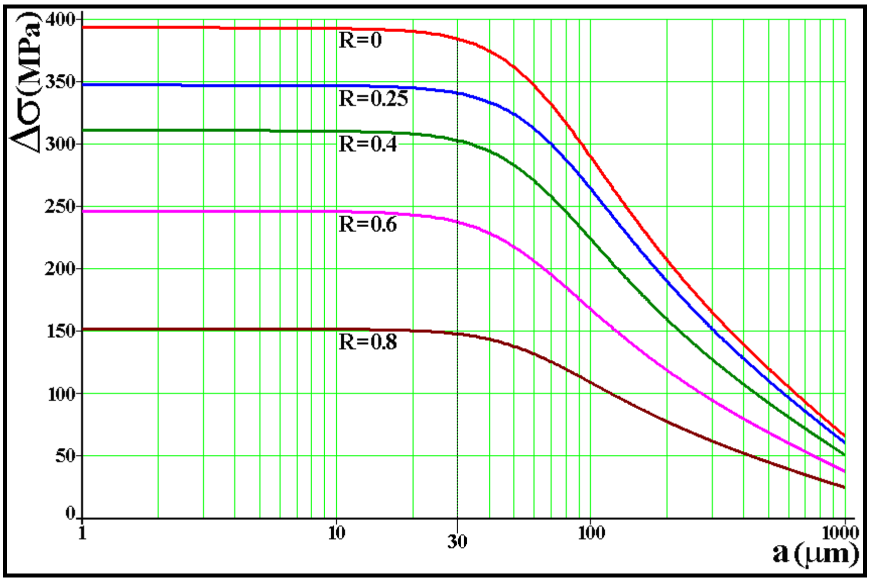


**Figure 3.** Larger stress ranges tolerable under several *R*–ratios for $w = 3.4mm$, $\eta = 1.12$, $\Delta K_{th0} = 6MPa\sqrt{m}$, $a_0 = 59\mu m$, $\gamma = 6$, and $\phi_F = 1.6$.

To model short 2D (mechanical) cracks that tend to grow both in depth and width in the simplest way, it is assumed that: (i) the cracks are loaded in pure mode I under quasi-constant $\Delta\sigma$ and *R* conditions, with no overloads or any other event capable of inducing load sequence effects; (ii) material properties measured testing 1D cracks in standard specimens such as $\Delta K_{thR}$ may be used to simulate FCG (or SCC) behavior of 2D cracks; and (iii) 2D surface or corner cracks can be well modeled as having an approximately elliptical front, thus their SIF can be described by the classical Newman-Raju equations [13]. If such reasonable hypotheses hold as expected, then the structural components tolerance to short or long fatigue cracks is given by:

$$\Delta\sigma < \begin{cases} \Delta K_{thR} \Big/ \left\{ \sqrt{\pi a} \cdot \Phi_a(a,c,w,t) \cdot \left[ 1 + (a_R/a)^{\gamma/2} \right]^{1/\gamma} \right\} \\ \Delta K_{thR} \Big/ \left\{ \sqrt{\pi c} \cdot \Phi_c(a,c,w,t) \cdot \left[ 1 + (a_R/c)^{\gamma/2} \right]^{1/\gamma} \right\} \end{cases} \quad (15)$$

The mode I SIFs at the tips of the semi-axes *a* along the depth and *c* along the width of semi-elliptical surface cracks in a plate of width *2w* and thickness *t* loaded under a pure tensile nominal load $\sigma$ are $K_I(a) = \sigma\sqrt{(\pi a)}\cdot\Phi_a = \sigma\sqrt{(\pi a)}\cdot F\cdot M/Q^{0.5}$ and $K_I(c) = \sigma\sqrt{(\pi a)}\cdot\Phi_c = \sigma\sqrt{(\pi a)}\cdot(F\cdot M/Q^{0.5})\cdot(a/c)\cdot G$ for $a < t$ and $c < w$, see [1, 9] for details.

---

* *Technical contribution to the 69th ABM International Annual Congress and to the ENEMET, July 21st -25th, 2014, São Paulo, SP, Brazil.*

ISSN 1516-392X

However, if the short 2D cracks start from notch tips, as usual, the stress analysis problem may be still more complex. In general they must include non-negligible 3D gradient effects around the notch tips, as discussed elsewhere [14]. On the other side, the tolerance to SCC cracks can be treated using these same principles, by properly changing the fatigue properties $\Delta K_{thR}$ and $\Delta S_{LR}$ by the corresponding material resistances to SCC cracking in the desired environment, $K_{ISCC}$ and $S_{SCC}$, as explained next.

## 4 NOTCH SENSITIVITY EFFECTS ON ENVIRONMENTALLY ASSISTED CRACKING

EAC is a time-dependent mechanical-chemical damage process due to the joint effect of tensile stresses and aggressive environments, which may induce crack nucleation and growth up to fracture under static loads well below those tolerable in benign media. As cracks only grow if driven by tensile stresses, the environment contribution is to decrease the material resistance to the cracking process. That is why the stress crack corrosion SCC notation is preferred here if there is no need to separate the various EAC mechanisms. Such problems are important for many industries, because costs and delivery times for SCC-resistant alloys are large and keep increasing. Major SCC problems occur e.g. in the oil industry, since oil and gas fields can contain considerably amounts of $H_2S$ which may attack steel pipelines, and in the aeronautical industry, when their light Al structures must operate in saline environments, like in carriers, offshore platforms, or costal airports.

For structural analysis purposes most SCC problems have been treated so far by a simplistic over-conservative policy on susceptible material-environment pairs: when aggressive media are unavoidable during the service lives of sensible components, the standard solution is to use a material resistant to SCC in those media to build them. A similar but less expensive alternative solution is to recover the structural component surface with a suitable nobler coating, if such a coating is available. SCC-proof coatings must be properly adherent, scratch resistant, and more reliable than common corrosion-resistant coatings, because structural components can fail without warning under such conditions. However, albeit over-conservative design criteria may be a nice way to avoid troubles, they can also be too expensive if an otherwise attractive material is summarily disqualified in the design stage when it may suffer SCC in the service environment, without considering any stress analysis issues.

In other words, pass/fail environment-based design criteria may cause severe cost penalties, as no crack can grow unless driven by tensile stresses. Indeed, SCC damage cannot be properly evaluated neglecting the influence of the stress fields that drive them, which must of course include both the stresses induced by service loads and the residual stresses eventually caused by previous loads and overloads, or else by maintenance or manufacturing processes. Moreover, although EAC conditions may be difficult to define in practice due to the number of metallurgical, chemical, and mechanical variables that may affect them, sound structural integrity assessment procedures must include proper stress analyses techniques for estimating maxima tolerable flaw sizes. Such techniques are important in the design stage, but they are even more useful to evaluate structural components not originally designed for SCC service, when by any reason they must pass to work under such conditions due to some unavoidable operational change, like e.g. a regular pipeline that must transport originally unforeseen amounts of $H_2S$ due to changes in oil well conditions while a new one specifically designed for such a service is built and

ISSN 1516-392X

commissioned. Economical pressures to take such a structural risk may be inescapable, since loss of profits associated with the very long time required for substituting a pipeline can be too huge, especially in offshore applications.
Such risky decisions can in principle be tamed by the methodology proposed following, which extends to EAC problems the analysis developed to model notch sensitivity effects in fatigue properly considering the behavior of short cracks [1-2]. To start with, if cracks behave well under SCC conditions, i.e. if Fracture Mechanics concepts can be used to describe them, then a "short crack characteristic size under SCC conditions" can be defined by:

$$a_{0SCC} = (1/\pi)\cdot(K_{ISCC}/\eta\cdot S_{SCC})^2 \quad (16)$$

This idea supposes that all chemical effects related to the environment-material pair behavior in SCC can be properly described and quantified by the material resistances to crack initiation and propagation in the service medium under fixed stress conditions, $S_{SCC}$ and $K_{ISCC}$, if such pairs remain fixed. Such properties are well defined and can be measured by standard procedures [1]. Note that although SCC problems are time-dependent, $S_{SCC}$ and $K_{ISCC}$ are not, as they quantify limit stresses required for starting environmentally assisted cracking. So, supposing that the mechanical parameters that limit SCC damage behave analogously to the equivalent parameters $\Delta K_{thR}$ and $\Delta S_{LR}$ that limit fatigue damage, a Kitagawa-like diagram can be proposed to quantify the crack sizes **a** tolerable by any given structure that works in SCC conditions under a given tensile stress $\sigma$. This idea makes sense as well if $K_{ISCC}$ and $S_{SCC}$ are viewed as the limits for $\Delta K_{th}(R)$ and $\Delta S_L(R)$ as $R \rightarrow 1$. It can be used e.g. to propose a generalized Kitagawa diagram with four regions that may contain non-propagating cracks, see Fig. 3. First, the lower region bounded by $\Delta S_L(R)$, the resistance to crack initiation, and $\Delta K_{th}(R)/\sqrt{(\pi a)}$, the resistance to large crack growth by fatigue in an aggressive environment, which limit the material tolerance to non-propagating fatigue cracks under fixed range loads at a given $R$-ratio in that medium; second, the region bounded by $S_{SCC}$ and $K_{ISCC}/\sqrt{(\pi a)}$ that may contain non-propagating SCC cracks in that medium; third, the region bounded by $\Delta S_{Lvac}$ and $\Delta K_{thvac}$, the $R$-independent fatigue limit and FCG threshold of the given material in vacuum, which limits its intrinsic resistance to non-propagating fatigue cracks; and fourth, the region limited by the intrinsic material properties $S_{Uvac}$ and $K_{ICvac}/\sqrt{(\pi a)}$, which can only be measured in vacuum or in truly inert environments. The advantage of looking at the cracking problem in such an integrated way is that this approach makes natural the attempt to treat mechanical and chemical damage under a unified analysis procedure such as Vasudevan and Sadananda's UA methodologies [9].
So, assuming that (i) cracks loaded under SCC conditions behave as expected, i.e. their driving force is indeed the SIF applied on them, and (ii) the chemical effects that influence their behavior can be described by the material resistance to crack initiation from smooth surfaces quantified by $S_{SCC}$ and by its resistance to crack propagation measured by $K_{ISCC}$; then it can be expected that, exactly as in the fatigue case, cracks induced by SCC may depart from sharp notches and then stop, due to the stress gradient ahead of such notch tips, eventually becoming non-propagating cracks. In such cases, the size of the non-propagating short cracks can be calculated using the same procedures useful for fatigue, and the tolerance to such defects can be properly quantified using an SCC notch sensitivity factor in structural integrity

* *Technical contribution to the 69th ABM International Annual Congress and to the ENEMET, July 21st -25th, 2014, São Paulo, SP, Brazil.*

ISSN 1516-392X

assessments. Therefore, for any given crack size **a**, a criterion for the maximum tolerable stress under SCC conditions can be proposed as:

$$\sigma_{max} \leq \frac{K_{ISCC}}{\sqrt{\pi a} \cdot g(a/w) \cdot \left[1 + (a_{0SCC}/a)^{\gamma/2}\right]^{1/\gamma}}, \quad a_{0SCC} = \frac{1}{\pi}\left[\frac{K_{ISCC}}{\eta \cdot S_{SCC}}\right]^2 \quad (17)$$

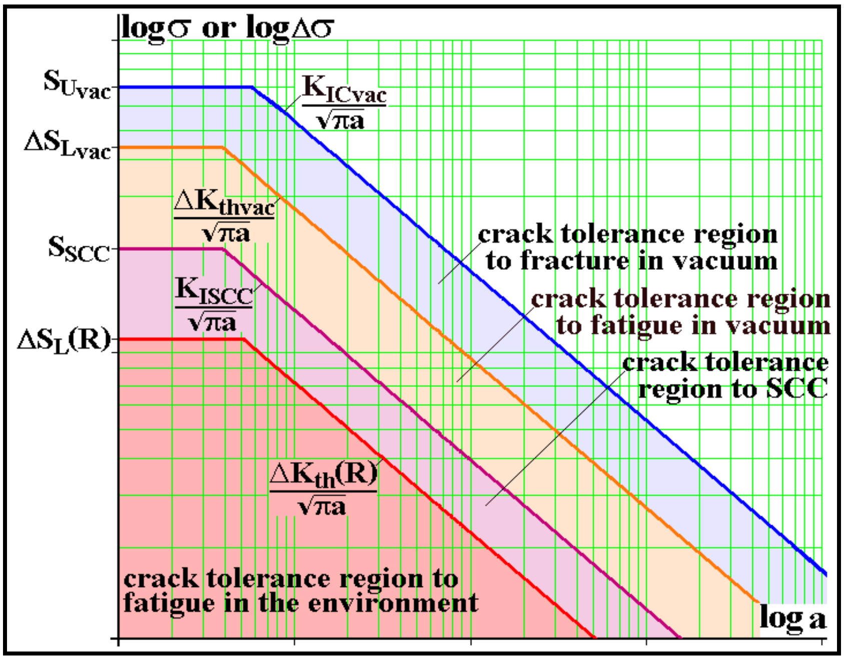


**Figure 4.** Generalized Kitagawa diagram showing fatigue and SCC limiting conditions for crack growth, including the contribution of mechanical stresses (inclusive residual ones) and of the strength reductions caused by the environment-material chemistry.

Likewise, a "notch sensitivity factor under EAC conditions" can be defined by

$$q_{SCC}(\kappa,\gamma) \equiv [K_{tSCC}(\kappa,\gamma) - 1]/(K_t - 1) \quad (18)$$

where $q_{SCC}$ and $K_{tSCC} = 1 + q_{SCC}(K_t - 1)$ are the notch sensitivity and the effective stress concentration factor under EAC conditions, which in this way can be seen as analogous to the $q$ and $K_f$ parameters used for stress analyses under fatigue conditions. Such equations allow stress analyses under EAC conditions and can be used for structural design purposes. Hence they can possibly substitute the pass/non-pass criterion used to "solve" most practical EAC problems nowadays. Indeed, they are the bases for a *mechanical* criterion for SCC that can be applied even by structural engineers, since it does not require expertise in chemistry to be useful. Moreover, it can be properly tested, as follows.

## 5 EXPERIMENTAL VERIFICATION

First, following expert advice (Vasudevan A, private communication), the basic SCC resistances were measured for the Al 2024 **–** liquid gallium pair (Ga is liquid above 30ºC, but curiously it only boils at 2204ºC). The main advantage of this exotic material-environment pair is its very quick SCC (in fact, LME) reactions, in the order of minutes. In comparison, SCC-sensitive Al alloys may take weeks to crack in NaCl-water solutions. Moreover, contrary to other liquid metals that may cause LME like mercury, Ga is a safe, non-toxic material.

ISSN 1516-392X

This 2024 T351 Al alloy was received as a rolled 12.7mm thick plate, with analyzed composition in weight %: Al + 4.44Cu, 1.35Mg, 0.54Mn, 0.18Zn, 0.16Fe, 0.12Si, 0.02Cr, 0.01Zr, and less than 0.05 of other elements. However, the alloy had to be annealed to remove its residual stresses, since in the original as-received plate condition the Ga induced the specimens to break during manipulation. All specimens were cut on the plate TL direction, identified by metallographic procedures. The basic mechanical properties of the annealed 2024 Al alloy were measured by ASTM E8M standard procedures at 35ºC, resulting in $E = 70GPa$, $S_Y = 113MPa$, $S_U = 240MPa$, and ultimate $\varepsilon_U = 16\%$.
SCC sensibility and reaction rates of the Al-Ga pair were qualitatively evaluated also at 35ºC in very slow $d\varepsilon/dt = 4.5 \cdot 10^{-8}/s$ strain rate tension tests made in modern servo-controlled electromechanical testing machines, following ASTM G129 and NACE standard recommendations. The liquefied Ga was applied on the test specimens surfaces with a brush, and light bulbs were used to maintain the warm 35ºC temperature during the tests. To guarantee that the exposure time was long enough to ensure the full LME reactions, the time necessary to propagate a crack in the annealed Al 2024 – liquid Ga pair was double-checked by testing pre-cracked C(T) specimens like those used to measure $K_{ISCC}$.
Two such specimens were tested under $7.5MPa\sqrt{m}$, and two others under $12MPa\sqrt{m}$. The latter failed in less than 3 hours, while the others did not fail after 2 days. So, following standard procedures and assuming that the incubation time should be a value close to 3 hours, a preload of $7.5MPa\sqrt{m}$ was applied for 1 day on the test specimens used to measure $K_{ISCC}$. Similarly, a pre-load of $30MPa$ was applied for 1 day on the test specimens used to measure $S_{SCC}$.
Such basic SCC resistances were measured using incremental load steps induced by calibrated load rings following ASTM E1681, ASTM F1624, and ISO 7539 standard procedures: $S_{SCC}$ tests started at $30MPa$ and used $2.5MPa$ steps and $K_{ISCC}$ tests initiated at $7.5MPa\sqrt{m}$ and used $0.25MPa\sqrt{m}$ steps. The time between successive load steps was at least one hour. The measured values were $S_{SCC} = 43.6 \pm 4.2$ MPa (average of 9 samples, with 95% reliability) and $K_{ISCC} = 8.8 \pm 0.3$ $MPa\sqrt{m}$ (8 samples, 95% reliability).
Finally, using such standard SCC properties, four pairs of C(T)-like notched test specimens were *designed* to support a maximum local stress $\sigma \cong 90MPa > 2S_{SCC}$ at their notch tips. The dimensions chosen for such notches were $\{b, \rho, b/w\} = \{20mm, 0.5mm, 0.33\}$, $\{12mm, 0.5mm, 0.2\}$, $\{20mm, 0.2mm, 0.33\}$, $\{40mm, 4.5mm, 0.67\}$, respectively for specimens TS1-TS2, TS3-TS4, TS5- TS6, and TS7-TS8, where $b$ and $\rho$ are the notch depth and tip radius, and $w$ is the specimen width, with both $b$ and $w$ measured from the load line. The idea was, of course, to study their SCF/stress gradient combinations in order to assure tolerance to the short cracks that should start at the tips of their notches, since they were loaded well above $S_{SCC}$. The (different) loads applied on each one of such notched test specimens were maintained for at least 48 hours.
Despite being submitted to a much longer exposure than that required to measure $S_{SCC}$ and $K_{ISCC}$ according to standard procedures, none of such notched specimens failed during the tests, exactly as predicted beforehand, in spite of being tested under a maximum local stress at the notch tip higher than twice the material resistance to crack initiation under SCC conditions, $\sigma_{max} > 2 \cdot S_{SCC}$, for a time period 50 times longer than the one required for the standard $S_{SCC}$ measurements. For further details, see [1].

## 6 CONCLUSIONS

A generalized El Haddad-Topper-Smith parameter was used to model the dependence of the threshold stress intensity range for short fatigue cracks on the crack size, as well as the behavior of non-propagating cracks induced by environmentally assisted corrosion (EAC). This dependence was used to estimate the notch sensitivity factor *q* of shallow and of elongated notches both for fatigue and for EAC conditions, from the propagation behavior of short non-propagating cracks that might initiate from their tips. It was found that the notch sensitivity of elongated notches has a very strong dependence on the notch aspect ratio, defined by the ratio *c/b* of the semi-elliptical notch that approximates the actual notch shape having the same tip radius. These predictions were calculated by numerical routines, and verified by proper experiments. Based on this promising performance, a criterion to evaluate the influence of small or large surface flaws in fatigue and in environmentally assisted cracking problems was proposed. Such results indicate that notch sensitivity can indeed be properly treated as a mechanical problem.

### Acknowledgments

CNPq granted research scholarships for the authors; Dr. A.Vasudevan, formerly from the Office of Naval Research (ONR) of the US Navy, has contributed with many stimulating discussions; and ONR provided a grant to partially support this work, under the supervision of Dr. W.C.Nickerson.

## REFERENCES

1 Castro JTP, Landim RV, Leite JCC, Meggiolaro MA. Prediction of notch sensitivity effects in fatigue and EAC. FFEMS, doi: 10.1111/ffe.12156, 2014.
2 Castro JTP, Leite JCC. Does notch sensibility exist in environmentally assisted cracking (EAC)? J Mat Res Technology. 2013;2:288-295.
3 Atzori B, Lazzarin P, Meneghetti G. A unified treatment of the mode I fatigue limit of components containing notches or defects. Int J Fract. 2005;133:61-87.
4 El Haddad MH, Topper TH, Smith KN. Prediction of non-propagating cracks. Eng Fract Mech. 1979;11:573-584.
5 El Haddad MH, Smith KN, Topper TH. Fatigue crack propagation of short cracks. *J Eng Mater Technology* 101, 42-46, 1979.
6 Yu MT, Duquesnay DL, Topper TH. Notch fatigue behavior of 1045 steel. Int J Fatigue. 1988;10:109-116.
7 Peterson RE. Stress Concentration Factors. Wiley; 1974.
8 Frost NE, Marsh KJ, Pook LP. Metal Fatigue. Dover; 1999.
9 Meggiolaro MA, Miranda ACO, Castro JTP. Short crack threshold estimates to predict notch sensitivity factors in fatigue. Int J Fatigue. 2007;29:2022–2031.
10 Barsom JM, Rolfe ST. Fracture and Fatigue Control in Structures. ASTM; 1999.
11 Castro JTP, Meggiolaro MA. Fadiga - Técnicas e Práticas de Dimensionamento Estrutural sob Cargas Reais de Serviço, Volumes I e II. CreateSpace; 2009.
12 Chapetti MD (2008). Fatigue assessment using an integrated threshold curve method – applications. *Eng Fract Mech* 75, 1854-1863.
13 Newman JC, Raju I. Stress-intensity factor equations for cracks in 3D finite bodies subjected to tension and Bending Loads, NASA TM-85793, 1984.
14 Góes RCO; Castro JTP; Martha LF. 3D effects around notch and crack tips. Int J Fatigue. 2013;62:159-170.