TOLERANCE TO FATIGUE AND TO SCC CRACKS

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Abstract. *Semi-empirical notch sensitivity factors q have been used for a long time to quantify notch effects in fatigue design. Recently, this old concept has been mechanically modeled using sound stress analysis techniques which properly consider the notch tip stress gradient influence on the fatigue behavior of mechanically short cracks. This mechanical model properly calculates q values from the basic fatigue properties of the material, its fatigue limit and crack propagation threshold, considering all the characteristics of the notch geometry and of the loading, without the need for any adjustable parameter. This model's predictions have been validated by proper tests, and a criterion to accept tolerable short cracks has been proposed based on it. In this work, this criterion is extended to model notch sensitivity effects in environmentally assisted cracking conditions.*

Keywords*: Short cracks; Non-propagating cracks; Environmental effects; Notch sensitivity*

1. INTRODUCTION

As fatigue is associated to two driving forces, one for cyclic and the other for static damage mechanisms, fatigue crack growth (FCG) rates on any environment depend on ΔK and K_{max}, the stress intensity factor (SIF) range and maximum, or on any other equivalent pair of parameters, such as ΔK and $R = K_{min}/K_{max}$. Even though R is not a crack driving force, such definitions are convenient for operational reasons. Long cracks grow by fatigue under fixed $\{\Delta K, R\}$ loading conditions if the applied SIF range ΔK is higher than the FCG threshold at the given R-ratio, $\Delta K_{th}(R) = \Delta K_{thR}$. Cracks may be considered *short* while their FCG thresholds are smaller than the long crack FCG threshold, thus while they can grow under $\Delta K < \Delta K_{thR}$ (since otherwise the stress ranges $\Delta\sigma$ required to propagate short cracks at a given R would be higher than their fatigue limits $\Delta S_L(R) = \Delta S_{LR}$ at that R-ratio) (Lawson et al., 1999). Such statements assume that the stresses are induced by external loads only, but 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 ΔK.

Mechanically short cracks larger than the grain with sizes may be modeled by LEFM concepts if the stress field that surrounds them is predominantly linear elastic, and if the material can be treated as isotropic and homogeneous in such a scale. Since 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, and then the notch sensitivity predictions based on it are corroborated by proper experiments. Finally, such concepts are extended to model notch sensitivity effects under environmentally assisted cracking conditions.

2. THE BEHAVIOR OF SHORT CRACKS IN FATIGUE

To reconcile the traditional fatigue (crack initiation) 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. (1979) added to the physical crack size a hypothetical *short crack characteristic size* a_0, a stratagem that forces the SIF of all cracks, short or long, to obey the correct FCG limits:

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

In this way, long cracks with $a >> a_0$ do not grow by fatigue if $\Delta K_I = \Delta\sigma\sqrt{(\pi a)} < \Delta K_{th0}$, while very small cracks with $a \to 0$ do not grow if $\Delta\sigma < \Delta S_{L0}$, since $\Delta K_I = \Delta\sigma\sqrt{(\pi a_0)} < \Delta S_{L0}\sqrt{(\pi a_0)} = \Delta K_{th0}$ in this case. Moreover, as the generic SIF is given by $K_I = \sigma\sqrt{(\pi a)}\cdot g(a/w)$, Yu et al. (1988) generalized Eq. (1) redefining the short crack characteristic size by:

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

Hence, if $a << a_0$, $\Delta K_I = \Delta K_{th0} \Rightarrow \Delta\sigma \to \Delta S_{L0}$, but when the crack starts from a notch, as usual, its driving force is the stress range $\Delta\sigma$ at the notch root, not the nominal 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, 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 root, which for microcracks tends towards K_t, i.e. $\varphi(a \to 0) \to K_t$, while the constant η quantifies the effect of the other parameters that affect K_I, such as the free surface. In this way, it is better to redefine a_0 by:

$$\Delta K_I = \eta \cdot \varphi(a) \cdot \Delta\sigma_n \sqrt{\pi(a+a_0)}\text{, where } a_0 = (1/\pi)\cdot\left[\Delta K_{th0} / \left(\eta \cdot \Delta S_{L0}\right)\right]^2 \tag{3}$$

The stress gradient effect quantified by $\varphi(a)$ does not affect a_0 since the stress ranges at notch tips must be smaller than the fatigue limit to avoid cracking, $\Delta\sigma(a \to 0) = K_t\,\Delta\sigma_n = \varphi(0)\Delta\sigma_n < \Delta S_{L0}$. However, since SIFs are crack driving forces, they should be material-independent. Hence, the a_0 effect on the short crack behavior should be used to 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

$$\frac{\Delta K_{th0}(a)}{\Delta K_{th0}} = \frac{\Delta\sigma\sqrt{\pi a}\cdot g(a/w)}{\Delta\sigma\sqrt{\pi(a+a_0)}\cdot g(a/w)} = \sqrt{\frac{a}{a+a_0}} \Rightarrow \Delta K_{th0}(a) = \Delta K_{th0}\left[1+(a_0/a)\right]^{-1/2} \tag{4}$$

For $a >> a_0$ this short crack FCG threshold tends to ΔK_{th0} and becomes independent of the crack size, as it should. It may be convenient to assume that Eq. (4) 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 γ proposed by Bazant (1997) to obtain:

$$\Delta K_{th0}(a) = \Delta K_{th0}\left[1+\left(a_0/a\right)^{\gamma/2}\right]^{-1/\gamma} \tag{5}$$

This equation reproduces the original ETS model when $\gamma = 2$, as well as the bilinear limits $\Delta\sigma = \Delta S_{L0}$ and $\Delta\sigma = \Delta Kth_0/\sqrt{(\pi a)}$ when $\gamma \to \infty$. This additional parameter may allow a better fitting of experimental data, and most data on short cracks are contained by the curves generated using $\gamma = 1.5$ and $\gamma = 8$. However, as fatigue damage depends on two driving forces, Eq. (5) should be extended to consider the σ_{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 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:

$$\Delta K_{thR}(a) = \Delta K_{thR}\cdot\left[1+\left(a_R/a\right)^{\gamma/2}\right]^{-1/\gamma}\text{, where } a_R = (1/\pi)\left[\Delta K_{thR}/\left(\eta\cdot\Delta S_{LR}\right)\right]^2 \tag{6}$$

Albeit defect-free micro filaments (whiskers) can be made in lab conditions, structural components always contain tiny defects like inclusions, voids, scratches, etc., which in the worst case behave like small cracks. When the size of such small defects is not much smaller than a_0, their structural effects can thus be estimated assuming they behave as mechanically short cracks using LEFM concepts, as detailed by Castro et al. (2013, 2014) and explained following.

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

Classical SN and εN methods are 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 methods used to inspect 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. 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 εN 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

$$\Delta\sigma \le \Delta K_{thR} \Big/ \left\{\varphi_F \cdot\sqrt{\pi a}\cdot g(a/w)\cdot\left[1+\left(a_R/a\right)^{\gamma/2}\right]^{1/\gamma}\right\}\text{, where } a_R = (1/\pi)\left[\Delta K_{thR}/(\eta\,\Delta S_{LR})\right]^2 \tag{7}$$

Since the fatigue limit ΔS_{LR} includes the effect of microstructural defects inherent to the material, Eq. (7) complements it by describing the tolerance to cracks (small or not) that may occur in actual service conditions. Such estimates can be used e.g. to evaluate the effect of accidental damage on the surface of otherwise well-behaved components, but they have some limitations. They assume that the short crack grows unidimensionally (1D), but as they may be small compared to the component dimensions, they can really grow in two directions. Moreover, such estimates are valid only for cracks with both a and a_0 larger than the grain size gr. The local 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, but as the grains still cannot be mapped in practice, they cannot be properly used for structural engineering applications yet, see Castro et al (2013, 2014) for details.

The SIFs of small mechanical cracks that start at notches with depth b and tip radius ρ can be estimated by Inglis using $K_I \cong 1.12\sigma_n\cdot f_1(K_t, a)\sqrt{(\pi a)}$, where $f_1 = \sigma_y(x)/\sigma_n$ is the stress concentration perpendicular to the crack plane at the point $(x = b + a, y = 0)$ ahead of such tips induced by an ellipse with semi-axes b and c and notch tip radius $\rho = c^2/b$. If the ellipse axis $2b$ is centered at the x-axis origin and is perpendicular to the nominal stress σ_n, then (Schive 2001)

$$f_1 = \frac{\sigma_y(x=b+a, y=0)}{\sigma_n} = 1 + \frac{(b^2-2bc)(x-\sqrt{x^2-b^2+c^2})(x^2-b^2+c^2)+bc^2(b-c)x}{(b-c)^2(x^2-b^2+c^2)\sqrt{x^2-b^2+c^2}} \tag{8}$$

The stress gradient ahead of notch tips justifies the peculiar behavior of short cracks that start from sharp notches. The SIF of short cracks that start at such notch tips first grows fast with their growing sizes a, but after a small Δa increment they may stabilize or even decrease for a while before growing once again. Indeed, the term $\sqrt{a}$ that increases $K_I = 1.12\sigma\sqrt{(\pi a)}\cdot f_1$ can be overcompensated by the abrupt fall in f_1 near a notch tip. Such concepts can be used to evaluate the tolerance to fatigue cracks that start from such notches (Castro et al. 2012). Short cracks can be arrested whenever their SIFs, which are highly sensitive to the stress gradient ahead of the notch tips, become smaller than the short crack FCG threshold at the given R-ratio, which depends on the crack size a while it is not much larger than the characteristic short crack size a_R: $\Delta K_I(a) \le \Delta K_{thR}(a) \Rightarrow$ crack arrest.

The notch sensitivity q still is quantified for design purposes by empirical curves fitted to a few data points compiled by Peterson (1974) a long time ago. It is used to estimate fatigue limits measured under fixed $\Delta\sigma_n$ and R in notched test specimens with a stress concentration factor $K_t \ge K_f = 1 + q\cdot(K_t - 1)$. However, according to Frost et al. (1999), early data showing that small non-propagating fatigue cracks are found at notch tips if $\Delta S_{LR}/K_t < \Delta\sigma_n < \Delta S_{LR}/K_f$ goes back as far as 1949. It is thus reasonable to expect that q is related to the fatigue behavior of short cracks emanating from notch tips. The notch sensitivity can in fact be calculated in this way using relatively simple but sound mechanical principles that do not require heuristic arguments, neither any arbitrary data-fitting parameter. To start with, according to Tada et al. (1985), the SIF of a crack with size a that departs from a circular hole of radius ρ is given within 1% by

$$\begin{cases} K_I = 1.1215\cdot\sigma\sqrt{\pi a}\cdot\varphi(x), \; x \equiv a/\rho \\ \varphi(x) = \left[1+\frac{0.2}{(1+x)}+\frac{0.3}{(1+x)^6}\right]\cdot\left[2-2.354\cdot\left(\frac{x}{1+x}\right)+1.206\cdot\left(\frac{x}{1+x}\right)^2-0.221\cdot\left(\frac{x}{1+x}\right)^3\right] \end{cases} \tag{9}$$

The FCG condition for cracks that start at such notch borders under pulsating loads is thus

$$\Delta K_I = \Delta\sigma\sqrt{\pi a}\cdot\eta\cdot\varphi(a/\rho) > \Delta K_{th0}(a) = \Delta K_{th0}\cdot\left[1+(a_0/a)^{\gamma/2}\right]^{-1/\gamma} \tag{10}$$

where $\Delta K_{th0} = \Delta S_{L0}\sqrt{(\pi a_0)} \equiv \Delta K_{th0}(a >> a_0)$, and $a_0 = (1/\pi)[\Delta K_{th0}/(\eta\cdot\Delta S_{L0})]^2$. This FCG criterion can be rewritten using two dimensionless functions, one related to the notch stress gradient $\varphi(a/\rho)$, and the other $g(\Delta S_{L0}/\Delta\sigma, a/\rho, \Delta K_{th0}/\Delta S_{L0}\sqrt{\rho}, \gamma)$, which includes the effects of the applied stress range $\Delta\sigma$, the crack size a, the notch tip radius ρ, the fatigue resistances ΔS_{L0} and ΔK_{th0}, and the optional data-fitting exponent γ (if it is used):

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

Figure 1 plots some φ/g functions for several fatigue strength-to-load stress range ratios $\Delta S_{L0}/\Delta\sigma$ as a function of the normalized crack length x, for a small notch radius comparable to the short crack characteristic size, $\rho \cong 1.40a_0$, and for $\kappa = \Delta K_{th0}/[\Delta S_{L0}\sqrt{(1.4a_0)}] = 1.12\sqrt{(\pi/1.4)} = 1.68$ and $\gamma = 6$. For high applied stress ranges $\Delta\sigma$, the strength-to-load ratio $\Delta S_{L0}/\Delta\sigma$ is small, and the corresponding φ/g curve is always higher than 1, so cracks will initiate and propagate from this small Kirsch hole border without stopping during this process, see $\varphi/g_{1.4}$ obtained for $\Delta S_{L0}/\Delta\sigma = 1.4$. On the other hand, small stress ranges with load ratios $\Delta S_{L0}/\Delta\sigma \ge K_t = 3$ have $\varphi/g < 1$, meaning that such loads cannot initiate a fatigue crack from this hole, and that small enough cracks introduced there by any other means will not propagate under such low loads. This is illustrated by the curves φ/g_3, associated with the limit case where the local stress range equals the material fatigue strength $\Delta S_{L0}/\Delta\sigma = 3$, and φ/g_4, associated with a still smaller load, $\Delta S_{L0}/\Delta\sigma = 4$.

Three other curves must be analyzed in Fig. 1. The $\varphi/g_{2.3}$ curve crosses the $\varphi/g = 1$ line once, thus such an intermediate load level can initiate and propagate a fatigue crack from this small Kirsch hole border, until the decreasing $\varphi/g_{2.3}$ ratio reaches 1, where the crack stops because the stress gradient ahead of its tip is sharp enough to eventually force $\Delta K_I(a) < \Delta K_{th}(a)$. Therefore, under this $\Delta\sigma = \Delta S_{L0}/2.3$ loading, a non-propagating fatigue crack is generated at this hole border, with a size given by the corresponding a/ρ abscissa where $\varphi/g_{2.3} = 1$. The $\varphi/g_{1.85}$ curve intersects the $\varphi/g = 1$ line twice. This load level also induces a fatigue crack at this Kirsch hole with $\rho \cong 1.40a_0$ border, which will propagate until reaching the maximum size obtained from the abscissa of the first intersection point (on the left), where the crack stops because it reaches $\Delta K_I(a) < \Delta K_{th0}(a)$. Moreover, cracks longer than the second intersection point will re-start propagating by fatigue under $\Delta\sigma = \Delta S_{L0}/1.85$, until eventually fracturing this Kirsch plate. However, the crack initiated by fatigue under such an intermediate pulsating load range cannot propagate between these two intersection points by fatigue alone, if the loading parameters $\{\Delta\sigma, \sigma_{max}\}$ remain constant. Hence, the crack can only grow in this region if helped by a different damage mechanism, such as SCC or creep.

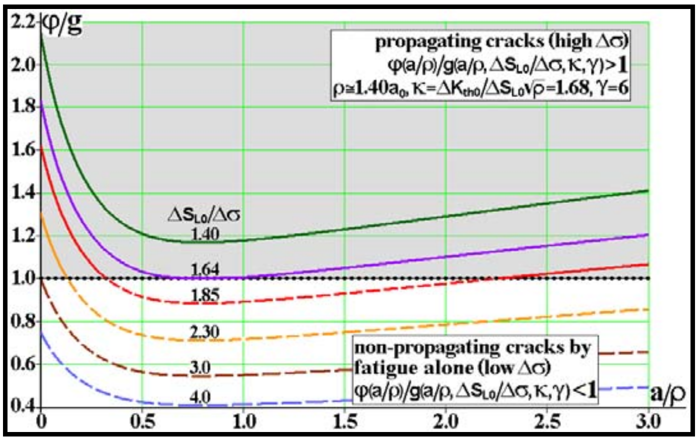

Fig. 1: Cracks that can start from the border of a (small) Kirsch hole with $K_t = 3$ may propagate by fatigue and then stop if their $\varphi/g < 1$ ($\rho \cong 1.40a_0$, $\kappa = 1.68$, and $\gamma = 6$ in this figure).

The FCG behavior of these two curves seems different in Fig. 1, yet they are similar. Indeed, the $\varphi/g_{2.3}$ curve crosses the $\varphi/g = 1$ line twice if the graph is extended to include larger cracks, since a long enough crack can always grow by fatigue under any given (even small) $\Delta\sigma$ range if its SIF range $\Delta K = \Delta\sigma\sqrt{(\pi a)}\cdot g(a/w)$ grows with the crack size a, as in this Kirsch plate. In fact, all φ/g curves eventually become high enough to propagate a crack for sufficiently large a/ρ values, even those that cannot initiate a crack by fatigue, such as φ/g_4. Finally, the $\varphi/g_{1.64}$ curve is tangent to the $\varphi/g = 1$ line in Fig. 1. Hence, this pulsating stress range $\Delta\sigma = \Delta S_{L0}/1.64$ is the smallest one that can cause crack initiation and growth (without arrest) from that notch border by fatigue alone. Hence, by definition, the fatigue SCF of this small Kirsch hole is $K_f = 1.64$, thus its notch sensitivity factor is $q = (K_f - 1)/(K_t - 1) = (1.64 - 1)/(3 - 1) = 0.32$. Moreover, the abscissa of the tangency point between the $\varphi/g_{1.64}$ curve and the $\varphi/g = 1$ line gives the largest non-propagating crack size that can arise from that hole by fatigue alone, a_{max}. For any other ρ/a_0, γ, and $\kappa = \eta\cdot\sqrt{(\pi a_0/\rho)}$ combination, K_f and a_{max} can always be found by solving the system

$$\begin{cases}\varphi/g = 1\\ \partial(\varphi/g)/\partial x = 0\end{cases} \Rightarrow \begin{cases}\varphi(x_{max}) = g(x_{max}, K_f, \kappa, \gamma)\\ \partial\varphi(x_{max})/\partial x = \partial g(x_{max}, K_f, \kappa, \gamma)/\partial x\end{cases} \tag{12}$$

Kirsch (circular) holes cause relatively mild stress gradients. Larger holes compared with the short crack characteristic size, $\rho >> a_0$, are associated to small $\kappa = \eta\cdot\sqrt{(\pi a_0/\rho)}$ values and do not induce short crack arrest. For example, Kirsch holes with $\rho > 7\cdot a_0$ in a material with $\gamma = 6$ do not induce non-propagating fatigue cracks under fixed pulsating loads, thus have $q = 1$. That is a sound mechanical interpretation for the notch sensitivity concept. If for a given γ Eq. (12) is solved for several notch tip radii ρ using $\kappa \equiv \Delta K_{th0}/\Delta S_{L0}\sqrt{\rho}$, then the notch sensitivity factor q is obtained by:

$$q(\kappa,\gamma) \equiv [K_f(\kappa,\gamma) - 1]/(K_t - 1) \tag{13}$$

This approach has four major assets: (i) it is an analytical procedure; (ii) it considers the effect of the fatigue resistances to crack initiation and propagation on q; (iii) it can use the exponent γ to generalize the original ETS model, but it does not need it neither any other data-fitting parameter; and (iv) it can be easily extended to deal with other notch geometries. For example, the SIF of cracks that depart from a semi-elliptical notch with semi-axes b and c, with b in the same direction of the crack a, which is perpendicular to the (nominal) stress $\Delta\sigma$, can be described by:

$$\Delta K_I = \eta\cdot F(a/b, c/b)\cdot\Delta\sigma\sqrt{\pi a} \tag{14}$$

where $\eta = 1.12$ is the free surface factor and $F(a/b, c/b)$ is the factor associated to the notch stress concentration effect. Using $s = a/(a + b)$, two expressions for $F(a/b, c/b)$ were introduced by Meggiolaro et al. (2007) by fitting a series of finite elements (FE) analyses for several types of semi-elliptical notches:

$$\begin{cases}F(a/b, c/b) \equiv f(K_t, s) = K_t\sqrt{[1 - exp(-K_t^2\cdot s)]/(K_t^2\cdot s)}, \ \ c \le b\\ F(a/b, c/b) \equiv f'(K_t, s) = K_t\sqrt{\dfrac{1 - exp(-K_t^2\cdot s)}{K_t^2\cdot s}}\cdot[1 - exp(-K_t^2)]^{-s/2}, \ \ c \ge b\end{cases} \tag{15}$$

Analyzing the life improvements introduced by stop-holes carefully made ahead of fatigue crack tips, Castro et al. (2012, 2013, 2014) present fatigue crack re-initiation data that support the notch sensitivity predictions made by this methodology.

4. NOTCH SENSITIVITY EFFECTS ON ENVIRONMENTALLY ASSISTED CRACKING

Environmentally assisted cracking (EAC) involves the nucleation and/or propagation of cracks in susceptible materials immerged in aggressive media. This time-dependent chemical/mechanical damage mechanism may lead to fracture under static tensile stresses that may be well below the material strength in benign environments. EAC mechanisms have a common feature: unlike other corrosion problems, they depend both on the environment/material pair and on the stress state, since cracks cannot grow unless loaded by tensile stresses. Indeed, cracks only grow if driven by tensile stresses, and the environment contribution is to decrease the material resistance to the cracking process (Vasudevan and Sadananda 2009, 2011). As the terminology *stress corrosion cracking* (SCC) enhances this mutual dependence, it is used here to name all EAC mechanisms when there is no need separate them. Such problems are important for many industries, because costs and delivery times for special SCC-resistant alloys are large and keep increasing.

However, for structural design purposes, most SCC problems have been treated so far by a simplistic policy on susceptible material-environment pairs: if aggressive media are unavoidable during a component life, the standard solution is to choose a material resistant to SCC in such media to build it. Such over-conservative design criteria may be safe, but they can also be too expensive if an otherwise attractive material is summarily disqualified in the design stage without considering any stress analysis issues. Decisions based on such an inflexible pass/fail approach may cause severe cost penalties, since no crack can grow unless driven by a tensile stress caused by the service loads and by the residual stresses induced by previous loads and overloads.

In other words, 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 analysis techniques for calculating maximum tolerable flaw sizes. Such techniques are important in the design stage, but they are even more useful to evaluate operating structural components not originally designed for SCC service, when by any reason they must work under such conditions due to some unavoidable operational change (e.g. to transport originally unforeseen amounts of H_2S due to changes in oil well conditions.) Economical pressures to take such a structural risk may be inescapable, but such risky decisions can in principle be controlled by the methodology proposed as follows, which extends to EAC problems the analysis developed to mechanically quantify notch sensitivity effects through the behavior of short fatigue cracks. Indeed, if cracks behave well under SCC conditions, i.e. if LEFM concepts can be used to describe them, then a "short crack characteristic size under SCC conditions" can be defined by:

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

In this way, assuming (as usual) that all chemical effects involved in SCC problems can be properly described and quantified by the traditional material resistances to crack initiation and propagation under fixed environmental and stress conditions, S_{SCC} and K_{ISCC}, the a_0 concept in SCC follows exactly the same idea of its analogous short crack characteristic size so useful for fatigue purposes: it uses the otherwise separated material resistances K_{ISCC} and S_{SCC} to describe the behavior of mechanically short cracks. Such resistances are well defined material properties for a given environment-material pair, and can be measured by standard procedures. Moreover, although SCC problems are time-dependent, S_{SCC} and K_{ISCC} are not, since they quantify the limit stresses required for starting or for growing cracks under SCC conditions. Hence, supposing that the mechanical parameters that limit SCC damage behave analogously to the equivalent parameters ΔK_{thR} and ΔS_{LR} that limit fatigue damage, a Kitagawa-like diagram can be used to quantify the crack sizes a tolerable by any given component that works under fixed SCC and (tensile) stress conditions, see Fig. 2.

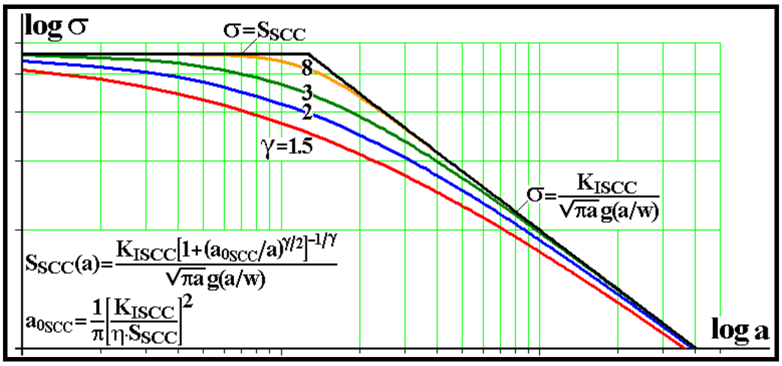

Fig. 2: A Kitagawa-Takahashi-like diagram proposed to describe the environmentally assisted cracking behavior of short and deep flaws for structural design purposes.

In other words, if cracks loaded under SCC conditions behave as they should, i.e. if their mechanical driving force is indeed the SIF applied on them; and if the chemical effects that influence their behavior are completely 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 cracks induced by SCC may depart from sharp notches and then stop, due to the stress gradient ahead of the notch tips, eventually becoming non-propagating cracks, exactly as in the fatigue case. In such cases, the size of non-propagating short cracks can be calculated using the same procedures used for fatigue, and the tolerance to such defects can be properly quantified using an "SCC notch sensitivity factor" in structural integrity assessments. Hence, a criterion for the maximum tolerable stress under SCC conditions can be proposed as:

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

In the same way, an expression analogous to Eq. (13) can be used to properly define a "notch sensitivity under EAC conditions" by solving for a given γ (if it is necessary to better fit the data) the system $\{\varphi/g = 1, \partial(\varphi/g)\partial x = 0\}$ for several notch tip radii ρ using $\kappa \equiv K_{ISCC}/(S_{SCC}\sqrt{\rho})$ to obtain

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

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. In this way, q_{SCC} and K_{tSCC} can be seen as analogous to the q and K_f parameters used for stress analyses under fatigue conditions. Such equations can be used for stress analyses of notched components under SCC conditions. Hence, they are potentially useful for structural design purposes when over-conservative pass/non-pass criteria used to "solve" most practical SCC problems nowadays are not affordable or cannot be used for any other reason. In fact, they can form the basis for a *mechanical* criterion for SCC that can be applied even by structural engineers, since it does not require much expertise in chemistry to be useful. Castro et al. (2013, 2014) present data to support such claim.

5. Conclusions

The dependence of the fatigue crack growth threshold on the crack size for short cracks and the behavior of non-propagating cracks induced by environmentally assisted corrosion (EAC) has been mechanically modeled and 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.

6. Acknowledgments

CNPq provided scholarships for Castro,JTP and Meggiolaro,MA; Dr. Vasudevan,A from ONR, the Office of Naval Research, US Navy, has contributed with many stimulating discussions; and ONR has partially support this research.

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