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On the tolerance to short cracks under fatigue and SCC conditions

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Abstract

The fatigue behavior of mechanically short cracks that depart from notch tips can be mechanically modeled using sound stress analysis techniques which properly account for the notch tip stress gradient influence on their growth rates, considering the basic fatigue properties of the material, its fatigue limit and long crack propagation threshold, and all the characteristics of the notch geometry and of the loading, without the need for any data fitting 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.

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1. Introduction

Fatigue crack growth (FCG) rates da/dN on any environment are driven by ΔK and K_{max}, the stress intensity factor (SIF) range and maximum, but they are frequently correlated with the equivalent pair ΔK and $R = K_{min}/K_{max}$ for operational reasons, even though R is not a crack driving force. Long cracks propagate by fatigue under fixed $\{\Delta K, R\}$ loading conditions when the applied SIF range ΔK is higher than the FCG threshold at the given R-ratio, $\Delta K_{th}(R) = \Delta K_{thR}$. Cracks are considered *short* while they can grow under $\Delta K < \Delta K_{thR}$ (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.) If the cracks start from notch tips or from smooth surfaces also loaded by residual stress fields, such resident stresses must be added to the externally applied stresses as static loading components that affect R but not ΔK.

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The fatigue behavior of mechanically short cracks, those larger than the parameter that characterizes the material intrinsic anisotropy such as their grain sizes e.g., can be modelled 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, LEFM techniques can then be used to develop a model for predicting the tolerance to mechanically short fatigue cracks. Such concepts can be extended to predict as well notch sensitivity effects under stress corrosion cracking (SCC) conditions.

2. The tolerance to short cracks under fatigue loads

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. [1] added to the 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:

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

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. [2] redefined the short crack characteristic size by:

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

Hence, if $a << a_0$, $\Delta K_I = \Delta K_{th0} \Rightarrow \Delta\sigma \to \Delta S_{L0}$. When the crack starts from a notch, as usual, its driving force is the stress range $\Delta\sigma$ at the notch tip, not the nominal range $\Delta\sigma_n$ used in SIF expressions. Since in such cases $g(a/w)$ includes the notch stress concentration effect, 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, $\varphi(a \to 0) \to K_t$, while 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:

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

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 [3]

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

For $a >> a_0$ this short crack FCG threshold tends to ΔK_{th0} independently 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 behaviours, introducing in the $\Delta K_0(a)$ definition an optional data fitting parameter γ to obtain [4]:

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

This equation reproduces the ETS model when $\gamma = 2$, and 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 modelled 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:

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

Structural components always contain tiny defects like inclusions, voids, scratches, etc., which behave like small cracks, so the tolerance to them can be estimated using LEFM concepts, if the size of such small defects is not much smaller than a_0. Classical *SN* and εN methods are used to 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 manufacturing or service. So, structural components should be designed to tolerate undetectable short cracks. As most long-life designs work just fine, 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 a tolerance to short crack requirement to their "infinite" life design criteria which, in its simplest version, may be given by [5]

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

3. The tolerance to short cracks under SCC conditions

Stress corrosion cracking (SCC) 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. SCC 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 [6-7].

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, 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 analyses. 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. However, if LEFM concepts can be used to describe them, then a "short crack characteristic size under SCC conditions" can be defined by [8]:

$$a_{0SCC} = (1/\pi) \cdot \left[K_{ISCC}/(\eta \cdot S_{SCC}) \right]^2 \quad (8)$$

Therefore, assuming (as usual) that all chemical effects involved in SCC problems can be 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 is analogous to the 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. 1.

In other words, 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:

$$\sigma_{max} \le K_{ISCC} \Big/ \left\{ \sqrt{\pi a} \cdot g(a/w) \cdot \left[1 + (a_{0SCC}/a)^{\gamma/2} \right]^{1/\gamma} \right\}, \; a_{0SCC} = (1/\pi)\left[K_{ISCC}/(\eta \cdot S_{SCC})\right]^2 \quad (9)$$

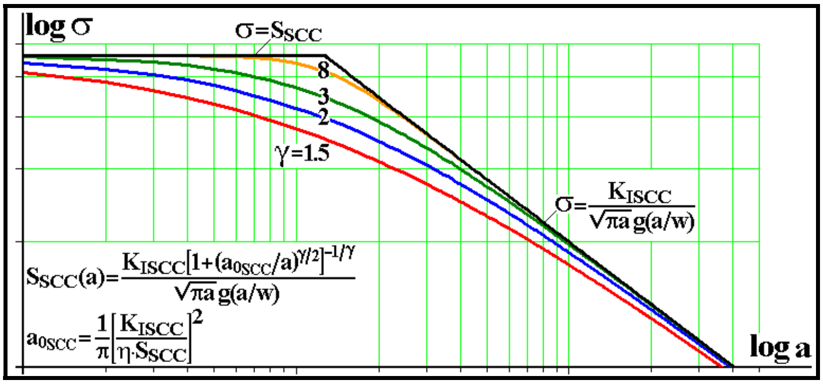

Fig. 1: A Kitagawa-Takahashi-like diagram proposed to describe the stress corrosion cracking behavior of short and deep flaws for structural design purposes.

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. [8] present data to support such claim.

4. 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 stress corrosion cracking has been mechanically modelled and used to estimate the notch and crack tolerance under fatigue and SCC conditions from the propagation behavior of short non-propagating cracks that might initiate from the notch tips. 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.

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