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A Review on the Fatigue Crack Propagation in the Threshold Region

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1. Introduction

The crack propagation has a well established equation by the so-called Paris-Erdogan relationship of log *da*/*dN x* log ΔK where *a* is the crack length, *N* is the number of cycles, and ΔK is the range of the stress-intensity factor in a loading cycle. In this curve, usually, three regions or crack growth regimes, A, B and C, can be identified. The Paris relationship is applied to the region B that shows a linear variation of log *da/dN x* log ΔK. In the Region C there is an upper limit; the material fracture toughness and in the Region A there is the lower limit (a threshold) so that below this threshold there is no crack growth.

This fatigue crack threshold, among other factors and variables, is also discussed as a function of some variables, including the material, the test conditions, the *R*-ratio, and the environment. ASTM E 647 defines the fatigue crack growth (FCG) threshold, ΔK_{th}, as that asymptotic value of ΔK at which *da*/*dN* approaches zero. For most materials an operational, although arbitrary, definition of ΔK_{th} is given as that ΔK value which corresponds to a fatigue crack growth rate of 10^{-10} m/cycle.

This paper, which is a revised and reduced version of a previous one [1], presents a review of the fatigue crack propagation threshold, ΔK_{th}, which is a very important parameter in some applications. In general it is not applied as it should be due to many reasons that include, among others, for instance, a conservative approach in design. The knowledge of the crack propagation law/rate in the threshold region is important due to the link between short and long cracks. The use of this parameter will based a new design criteria to help the development of structures with greater confidence level and less conservative approaches.

2. The Threshold

The earliest studies of fatigue, as did Wöhler [3], did not considered crack growth as a separate phenomenon, before rupture. The approach to evaluate the crack growth is simple for long cracks and it by passes the unknown details of crack tip atomistic processes. (Long cracks are those ones that start to grow (measurably) for a given cyclic loading.) For these it is possible to draw a curve da/dN vs. ΔK, Fig. 1. This well known curve is a function of the *R* load ratio and it is usually drawn on a log-log scale. Cracked materials are only superficially elastic.

However, there is always plasticity in a region very near the crack tip. Under linear elastic fracture mechanics LEFM this region is so small that it does not affect the overall cracked material behavior. As the near-threshold conditions involves relatively small (cyclic) loads we have the so-called small scale yielding conditions where the plasticity do not have a commensurate importance in predictive ability under near-threshold conditions except in special cases.

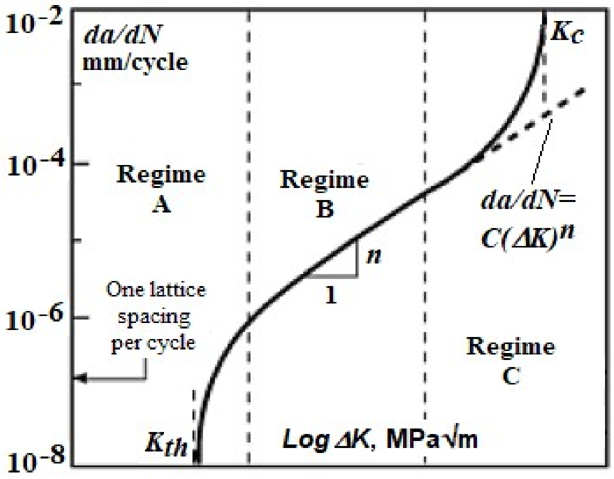

Figure 1: Fatigue Crack Propagation Regimes (Adapted from [2])

So, nowadays, with the tools of Fracture Mechanics (specifically LEFM) it is possible to analyze how cracks propagate under cyclic load. There are, even, several studies that try to simulate how cracks propagates under ductile regime (under plasticity), see [4], for instance. However this will not be mentioned in this review work. *Log ΔK*, MPa√m da/dN

From the Paris Law curve one can say that the threshold for crack propagation may not be an intrinsic part of the growth (e.g. Paris) relation. Usually the threshold values vary more with changing test conditions than do the Paris Law constants. However, within the threshold region, other *extrinsic* effects seem to dominate any *intrinsic* threshold itself. These *extrinsic* effects have been embraced under the heading of 'crack closure' when the effective stress intensity range is not the applied maximum stress intensity minus the applied minimum stress intensity, but rather the applied maximum stress intensity minus closure stress intensity. The growth of small cracks is even more complicated. Usually, in the case of small cracks, so within the threshold region, the crack propagation be fitted, as with a spline of local small-crack Paris relations [5,6,7].

3. The Effect of Crack Geometry

Considering a superficial crack the threshold region in metals is generally associated with a reversed-shear mode of growth which at least implies a mode II component. At the same time, plasticity is largely confined to select crystallographic planes, e.g. {111} in Fe–Ni alloys. This gives rise to a faceted fracture surface. Since growth is taking place by a shear mechanism on planes inclined to the mode I stress plane, a certain amount of mode II displacement is expected. If this were unreversed, as might happen in a tensile overload, registry of the peaks and troughs between the upper and lower crack faces could be lost and the peaks would contact each other before the crack fully closed.

At stress intensity ranges near the threshold, a large oxide buildup is likely. Several works on this subject are mentioned in [8]. The presence of this oxide, due to fretting, has been thought to crack open [9]. At very low fatigue loads, oxide, and at higher loads, misaligned facets act as wedges reducing the effective stress intensity range by preventing the crack from closing. These effects are called, respectively, oxide- and roughness-induced *crack closure*. In region close to the fatigue threshold, the stress ratio exerts a strong effect. Environmental effects similarly reach a maximum at stress intensity ranges near threshold but then diminish [10].

4. Crack Closure Models, the R-ratio Effect and Physical Mechanisms

In the early 1970s Elber proposed [11], the concept of crack closure to explain the influence of the *R* load ratio on fatigue crack growth (FCG). It has been realized for a long time that the amount of crack closure was higher at lower R [12] while it could be negligible at higher R (i.e., R > 0.7) [13]. As a result, instead of the conventional ΔK, the FCG rate was correlated with the effective stress intensity factor range ΔK_{eff} [13], i.e., $\Delta K_{eff} = K_{max} - K_{cl}$ Here, K_{max} is maximum stress intensity factor and K_{cl} is the stress intensity when crack is closed.

From then on, several models of crack closure were defined, particularly when the R-effect is associated with environment and temperature factors. Air humidity, corrosive and other gaseous environment were an additive contribution to the effect of R on FCG [14, 15]. Aqueous, moist and dry gaseous environments also have influence of R on near-threshold fatigue behavior [16] to a crack closure mechanism due to the crack face oxidation products. Also, temperature in both CrMoV and pressure vessel steels show to produce an R-effect [17].

In addition, some exponential models were applied to predict mean stress dependence on ΔK_{th}. For instance, Kwofie [18] proposed an exponential mean stress function based on the equivalent stress concept, and was further developed to a model that could predict ΔK_{th}, under lower R, reasonably well [19].

Another exponential model was proposed by Adib and Baptista [20] where the da/dN was related to the ΔK in an exponential form, eq. (1)., where α and β are material constants. Later, they developed a more enhanced model by taking the influence of R into account [21].

$$da/dN = e^{\alpha} e^{\beta/\Delta K} \tag{1}$$

Among the cited factors it has been found, also, that the effect of R on da/dN and ΔK_{th}, depends on microstructures, as well as test frequency and loading mode, among other factor. The mechanisms of R-effect of FCG can, also, be interpreted in terms of energy, cyclic deformation and fracture modes at crack tip. In [1] all these influences are described and detailed.

4. Conclusions

This paper presented and briefly discussed some topics regarding the threshold fatigue crack propagation, ΔK_{th},. As already mentioned, is a revised and reduced version of a previous review work [1] where the argument was developed and detailed. The effects of crack size, as well as crack geometry were mainly covered. The crack closure models presented to discuss the effect of load ratio R on fatigue crack propagation. Many other topics should be discussed with relation with threshold area like short crack models and their application. The main scope is to motivate the engineers to project structures with less conservative approach.

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