Chapter 23
Crack Propagation in the Threshold Stress Intensity Region a Short Review

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Abstract This work presents a short review of fatigue crack propagation with emphasis on the parameters that influence the threshold stress intensity, ΔKth. This threshold value is dependent on such variables as the material itself, the test conditions, the *R*-ratio, the environment and crack closure. The crack geometry effects are discussed as well as some crack closure models. A discussion of other parameters that influence the threshold stress intensity regime including short crack thresholds and their respective models and their application will be the subject of a near-future review.

Keywords Fatigue · Design · Threshold stress intensity factor · Crack propagation · Crack closure models

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23.1 Introduction

Modern defect—tolerance design approaches to fatigue are based on the premise that engineering structures are inherently flawed; the useful fatigue life then is the time or the number of cycles to propagate a dominant flaw from an assumed or measured initial size to a critical dimension. In most metallic materials, catastrophic failure is preceded by a substantial amount of stable crack propagation under cyclic load conditions.

The rates at which these cracks propagate for different combinations of applied stress, crack length and geometric conditions of the cracked structure, and the mechanisms which influence the crack propagation rates under different combinations of mean stress, test frequency and environment, are practical interest [1]. Crack propagation is usually described by the relationship/curve of log da/dN versus 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. As depicted in Fig. 23.1, one can identify three regions or crack growth regimes that this curve passes through, named Regions A, B and C. The Paris power law relationship can be applied to the region B that shows a linear variation of log da/dN versus log ΔK. The curve is bounded by two limits, the upper limit (in Region C) being the fracture toughness of the material and the lower limit (in the Region A) being the threshold. Below this threshold there is no crack growth. Several parameters/variables can have influence in this curve. The fatigue crack threshold is discussed by McEvily [2] as a function of a number of variables, including the material, the test conditions, the R-ratio, and the environment. ASTM E 647 defines the fatigue crack growth (FCG) threshold, ΔKth, as that asymptotic value of ΔK at which da/dN approaches zero. For most materials an operational, although arbitrary, definition of ΔKth is given as that ΔK value which corresponds to a fatigue crack growth rate of 10–10 m/cycle.

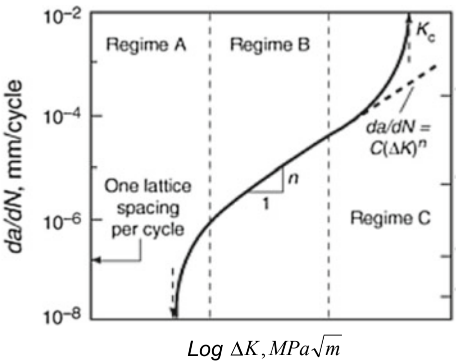

Fig. 23.1 Fatigue crack propagation regimes [2]

23.2 The Threshold Region

The earliest studies of fatigue were concerned with failure of a workpiece after a number of loading cycles. At that time, researchers, most significantly Woehler [3], did not isolate crack growth as a separate phenomenon, before rupture. The approach to evaluate crack growth is simple for long cracks and by passes the unknown details of crack tip atomistic processes (Long cracks are those ones that start growing for a given cyclic loading.). For these it is possible to draw a curve of crack propagation rate (da/dN) versus the range of the alternating stress intensity (ΔK). The curve itself (Fig. 23.1) is a function of R load ratio and it is usually drawn on a log-log scale. Cracked materials are only superficially elastic. There is always plasticity in a region very near the crack tip. Under LEFM this region is so small that it does not affect the overall cracked components stress distribution. Larger scale plasticity is explicitly described by elastic–plastic formulations such as the J-integral or the crack tip opening displacement (CTOD).

The variables K and J are, however, closely related under small scale yielding conditions; the additional work involved in using J has not appeared to yield a commensurate improvement in predictive ability under near-threshold conditions except in special cases. The relative success of LEFM is illustrated by Fig. 23.2 which shows the correlation of da/dN × ΔK for experimental data for a 2024—T3 aluminum alloy obtained by Paris et al. [4] and Paris and Erdogan [5] from various sources.

Nowadays, with the tools of Fracture Mechanics (specifically LEFM) it is possible to analyze how cracks propagate under cyclic load. Several studies try to simulate how cracks propagate under in a large scale plasticity regime, however this will not be mentioned in this review work. To know more about this regime one can see [6], for instance. Figure 23.1 suggests that the threshold for crack propagation may not be an intrinsic part of the growth (e.g. Paris) relation. For any given material, thresholds are apt to vary more with changing test conditions than do the Paris constants. But,

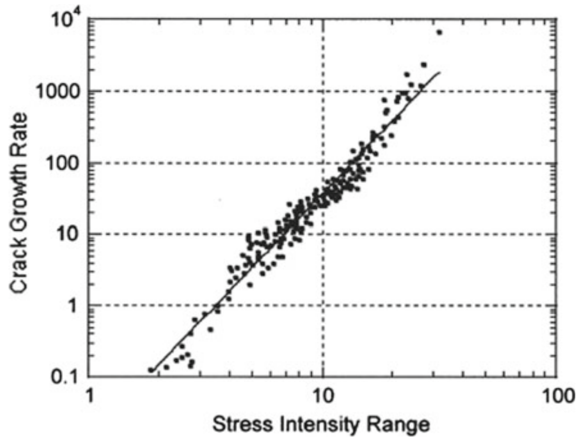

Fig. 23.2 Data for 2024-T3 aluminum from various sources used by Paris et al. [4] and Paris and Erdogan [5]

within the threshold region, extrinsic effects seem to modify the value of an intrinsic threshold. These extrinsic effects have been embraced under the heading of 'crack closure'. As defined by Elber, when closure is present, 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 a closure stress intensity. The growth of small cracks is even more complicated. It is not unusual in the case of small cracks for crack propagation within the threshold region to be fitted, as with a spline of local small-crack Paris relations defining the mean value of the growth rate for the given conditions [4, 5, 7].

23.3 Effect of Crack Geometry

Considering a small 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 [8].

This gives rise to a faceted fracture surface. Since growth takes 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 [9, 10]. The presence of this oxide, believed to be due to fretting, is thought to increase the crack opening stress [11–15]. 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 the region close to the fatigue threshold, the stress ratio exerts a strong effect on the crack closure level. Environmental effects similarly reach a maximum at stress intensity ranges near threshold but then diminish [11, 12].

23.4 Crack Closure Models

Since it was proposed by Elber [16] in the early 1970s, the concept of crack closure has been widely used to explain the influence of R load ratio on fatigue crack growth (FCG) [17, 18]. It has been realized for a long time that the degree of crack closure was higher at lower R [19] while it may be negligible at higher R values (i.e., $R > 0.7$) [20–22]. As a result, instead of the conventional ΔK, the FCG rate was correlated with the effective stress intensity factor range ΔK_{eff} [20, 21], 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. Since then, several crack closure mechanisms have been defined that include the effect of R, environment, temperature and crack growth mode. Stewart [23] reported that air humidity, corrosive and other gaseous environments provided additive contributions to the effect of R on FCG.

23.5 Conclusions

This paper reviewed and discussed some topics regarding the parameters that influence the threshold stress intensity value in crack propagation under cyclic loading. Among these parameters the effect of crack closure and R-ratio were the main focus of this review. Other topics related to the threshold stress intensity regime including short crack thresholds and the respective models and their applications will be the subject of a future review.

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