Small Fatigue Cracks: A Statement of the Problem and Potential Solutions

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ABSTRACT

The current status of the problem of small cracks in fatigue is presented. Several classes of small cracks are distinguished, and their individual characteristics described. Specifically, for cracks small compared with microstructural size scales, for cracks small compared with the extent of local plasticity or for cracks which are either chemically or physically small (e.g. about 1 mm or less), comments are made on the origins of differences in behavior between large and small cracks, on the question of the "driving force" for small crack advance and on the possible existence of intrinsic thresholds for crack growth. Finally, some thoughts are offered on the use of small-crack methodology in life prediction analyses and in alloy design.

1. INTRODUCTION

The total fatigue life of engineering structures and components is often dominated by the time (or number of cycles) during which incipient cracks are small (typically less than 1 mm) and propagating at low growth rates. However, it is in this regime that the behavior of such cracks may become non-unique and exhibit growth rates far in excess of those of long cracks (typically larger than 10 mm) subjected to the same nominal "driving force", *e.g.* the same stress intensity range [1-7].

In this paper, the salient features of the problem are evaluated with respect to the various classes of small cracks. In addition, some thoughts are offered on the incorporation of small-crack methodology into current design and fatigue life prediction analyses and on the development of new materials with superior resistance to the growth of microcracks by fatigue.

2. THE SMALL-CRACK PROBLEM

The small-crack problem is in essence one created by fracture mechanics through a breakdown in the similitude concept at small crack sizes [8]. For example, it has been shown [9] that crack tip strain fields for large and microstructurally small fatigue cracks, driven by nominally equivalent cyclic stress intensities, are qualitatively and quantitatively dissimilar. It is thus a problem of defining a flaw-size-independent "crack driving force" to account for observations that small cracks can propagate at rates different from those of corresponding long cracks at the same nominal driving force. In the large majority of cases, small-crack growth rates exceed those of long cracks, although there is evidence in steels of a mild reverse effect [10, 11]. Following initiation, small cracks are observed to grow at stress intensities below the long-crack threshold; some extend with decaying growth rates until arrest, while others propagate quite rapidly to merge with long-crack behavior (Fig. 1). The problem therefore has practical significance, because damage-tolerant fatigue lifetime computations are invariably based on long-crack data. As overall life is most influenced by low growth rate behavior, the accelerated and subthreshold extension of small flaws can lead to potentially dangerous over-predictions of life.

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3. DEFINITION OF A SMALL CRACK

Adjectives describing various types of small crack currently abound, although some consensus is emerging. For example, the distinction between (three-dimensional) small cracks and (two-dimensional) short cracks, the latter being small in all but one dimension, clearly is of importance [12, 13]. Short cracks are generally through-thickness flaws, no smaller than 50 μm, which are created artificially by removing the wake material from long through cracks. Their behavior appears to be dominated, like that of large cracks, by the cyclic stress intensity factor ΔK (for small-scale yielding), corrected by considerations of crack closure [13, 14]. Naturally occurring small cracks, conversely, often approach microstructural dimensions and, although their behavior is still largely affected by closure, several other factors, including crack shape [13, 15], enhanced crack tip plastic strains [12] and local arrest at grain boundaries [16, 17], are of comparable significance.

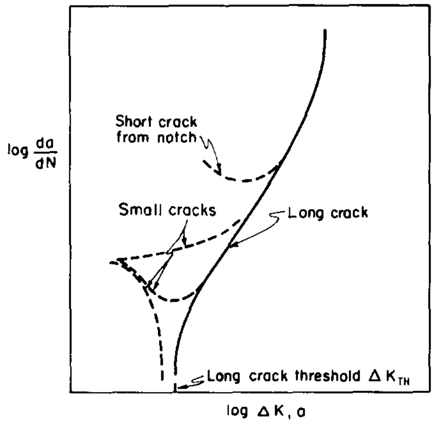

Fig. 1. Schematic representation of the typical variation in fatigue crack growth rates da/dN, with the nominal cyclic stress intensity factor ΔK, or crack length a, for "long" and "small" cracks (constant-amplitude loading; R = constant). ΔK_{TH} is the nominal threshold stress intensity range below which long cracks remain dormant.

Useful qualifiers remain microstructurally, mechanically and physically small (or short), which pertain respectively to cracks small compared with microstructural dimensions, to the scale of local plasticity and simply to cracks of a size less than 0.5–1 mm [4]. In addition, fatigue cracks have also been described, with reference to environmental effects, as chemically small [6, 18], as described below. Each of these classes of small flaw is associated with particular phenomena which primarily distinguish it from long-crack behavior (Table 1). For example, for mechanically small cracks, characterization in terms of elastic–plastic fracture mechanics (*e.g.* through the use of either the crack-tip-opening displacement or ΔJ [19, 20]), or even in terms of the strain energy density ΔS [21], may help to resolve differences in growth rates behavior between long and small cracks. However, for physically small cracks, allowance for differences in the magnitude of crack closure (*e.g.*

TABLE 1

Classes of small fatigue cracks

Type of small crack	*Dimension*	*Responsible mechanism*	*Potential solution*
Mechanically small	$a \lesssim r_y$ [a]	Excessive (active) plasticity	Use of ΔJ, ΔS or crack-tip-opening displacement
Microstructurally small	$a \lesssim d_g$ [b]	Crack tip shielding, enhanced $\Delta\epsilon_p$	Probabilistic approach
	$2c \lesssim (5\text{–}10)\,d_g$	Crack shape	
Physically small	$a \lesssim 1$ mm	Crack tip shielding (crack closure)	Use of ΔK_{eff}
Chemically small	Up to about 10 mm [c]	Local crack tip environment	

[a] r_y is the plastic zone size or plastic field of notch.
[b] d_g is the critical microstructural dimension, *e.g.* grain size, a is the crack depth and $2c$ the surface length.
[c] Critical size is a function of frequency and reaction kinetics.

through the use of ΔK_{eff}) appears to be the predominant correlating factor [2, 4, 14]. For microstructurally small cracks, all these factors may be important, plus others associated with local inhomogeneities in the microstructure, non-uniform growth, retardation at grain boundaries and so forth [10, 12].

In particular, the microstructurally small, rapidly growing crack corresponds to a three-dimensional flaw whose plastic zone is less than the key microstructural dimension, which in many cases has been related to the grain size. Here, the crack tip tends to operate as it would in a single crystal preferentially oriented for operation of the relevant crack extension mechanism. In addition, the crack front encompasses relatively few grains, so that growth is not averaged over many disadvantageously oriented grains. The latter is probably a major factor in distinguishing small cracks from short through-thickness cracks, whose fronts must necessarily sample many grains. It further provides an explanation of why crack tip shielding alone is generally sufficient to rationalize behavior of the short through crack.

4. ORIGINS OF DIFFERENCES BETWEEN LONG- AND SMALL-CRACK BEHAVIOR

Several major factors have been identified which are primarily responsible for differences in long- and small-crack behavior (Table 1). Of particular significance is the varying contribution of crack tip shielding, with the size of the crack wake, in locally reducing the effective driving force experienced at the tip [14]. Such shielding arises in fatigue from crack closure (see for example refs. 2 and 4) (and to a lesser extent from crack deflection [22]) and has been shown to be reduced at small crack sizes [13, 14]. However, for microstructurally small cracks, it is now apparent that closure does not provide the entire solution (although uncertainties in experimental measurement make this question difficult to resolve). There is now considerable evidence that, additionally, such cracks are impeded locally by grain boundaries [16, 17], influenced by non-uniform growth [13, 15], and may experience higher cyclic plastic strains at their tips [12]. Finally, differences in local crack tip environment with crack size provide the source of the chemically short-crack effect [18, 23], as described below.

5. ENVIRONMENTAL EFFECTS

One of the most complex issues involved in the small-crack problem is associated with (liquid) environmental effects. As outlined by Gangaloff and Wei [23], the chemically short crack may still propagate 1.5 to several hundred times faster than long cracks subjected to the same mechanical driving force. Moreover, it may be somewhat larger than the microstructurally or mechanically short flaw, as short-crack behavior has been reported for crack sizes of about 10 mm or more. (Precise definition of the size range for chemically short cracks depends on several factors but is principally controlled by frequency and reaction kinetics.) The discrepancy in behavior is attributed to differences in local crack tip chemical environment and conditions [6, 18, 23]. The critical issues thus pertain to the determination of crack tip conditions, as a function of crack length, in terms of the coupled processes of fluid transport and chemical–electrochemical reactions within the crack, and the determination of the origin of the environmentally enhanced cracking rates in relation to the hydrogen embrittlement and film rupture–dissolution mechanisms.

6. "DRIVING FORCE" FOR SMALL-CRACK PROPAGATION

Several researchers (see for example refs. 2–4, 13, 14, 19 and 20) have sought improved field characterizing parameters to describe the driving force for small-crack advance (Table 1). Although parameters such as $\Delta\sigma$ and $\Delta\epsilon_p$ have been suggested [3], only those parameters that can be measured globally and yet define (at least nominally) local conditions are reviewed here. For mechanically small cracks, where the extent of local plasticity is comparable with crack size, elastic–plastic fracture mechanics solutions have been proposed through the use of ΔJ [19, 20] and ΔS [21]. While certainly appropriate for taking account of excessive plasticity ahead of the tip, it should be noted that J is a non-linear elastic parameter and thus cannot account for the vital influence of wake plasticity (prior plastic zones) behind the tip. Similarly, the use of ΔS cannot account for the varying contribution from wake-related crack tip shielding. To allow for such wake effects, which principally cause crack closure, the adoption of a closure-corrected ΔK_{eff} ($= K_{max} - K_{cl}$ where K_{cl} is the closure stress intensity) appears to be a suitable approach for physically small cracks [13, 14] and cracks emanating from notches [24]. For microstructurally small flaws, however, such deterministic treatments may simply not apply, as initial cracking may center on local preferential growth sites ("soft spots") in the microstructure [12]. Here a probabilistic approach may be the optimum treatment to describe the behavior of such tiny flaws.

7. INTRINSIC THRESHOLDS

There is now good evidence that intrinsic threshold cyclic stress intensities may exist for long fatigue cracks. By subtracting out the contribution from crack closure through the use of the ΔK_{eff} parameter, threshold values at low load ratios approach those at high load ratios where closure effects are minimal (see for example refs. 14 and 25). Similarly, intrinsic thresholds may exist for physically and mechanically short cracks, of magnitude comparable with the effective long-crack value [13, 14, 26]. For microstructurally small cracks, however, the question of an intrinsic threshold may not be meaningful. Here the "fatal" cracks are those that initiate first at local "soft spots" in the microstructure. As their dimensions are well below any continuum approximation, characterization in terms of a material parameter clearly would be inappropriate. Further, in the light of evidence [12] suggesting the invalidity of ΔK within this flaw size regime, it may be more appropriate to consider a threshold stress, rather than a stress intensity, for microstructurally small flaws (*i.e.* akin to the fatigue limit).

8. SMALL-CRACK METHODOLOGY IN LIFE PREDICTION AND DESIGN

For physically or mechanically small cracks, the adoption of small-crack methodology in life prediction analyses appears to be feasible by mere extension of the current damage-tolerant procedures to smaller crack sizes through the use of ΔK_{eff} or an equivalent elastic–plastic characterizing parameter. Such an approach would greatly enhance projected lifetimes, as computations are dominated by the regimes where the crack is small and advancing slowly. Conversely, for the reasons outlined above, descriptions of the extension of microstructurally small flaws will not be generally amenable to deterministic analyses which rely on (continuum) material parameters and should be treated with probabilistic approaches.

9. SMALL-CRACK CONSIDERATIONS IN ALLOY DESIGN

From an alloy design perspective, the study of small cracks and associated long-crack thresholds has resulted in a far clearer understanding of the various contributions to fatigue resistance. Moreover, it has led to the realization that microstructural features which benefit resistance to the growth of (long) cracks may have an entirely different influence on crack initiation and small-crack growth. To impede long-crack growth, the primary mechanisms are extrinsic, whereby mechanical, microstructural and even environmental mechanisms are utilized to reduce locally the crack driving force [14]. Here, promotion of crack tip shielding, principally through crack closure and deflection, provides the most potent effect under cyclic loading. Conversely, to impede crack initiation and the early growth of microstructurally small cracks, where shielding effects are minimized, the primary mechanisms are intrinsic. For example, fine grain sizes offer best resistance to crack initiation and small-crack growth in many alloys (see for example ref. 27); yet in these same materials it is the coarse grain structures which promote the roughest crack paths and hence provide greatest resistance to long-crack growth (through crack deflection and roughness-induced closure) (see for example ref. 25).

In essence, the ideal alloy design approach is to clean up the material for optimum resistance to crack initiation, to incorporate small, randomly oriented grains to inhibit small crack growth and then to add microstructural "crack stoppers" through shielding mechanisms to impede long-crack growth. It may also be possible to minimize the small-crack problem by incorporating texture, so that as few grains as possible are oriented for easy crack extension relative to a known uniaxial loading axis.

10. CONCLUSIONS

(1) Small fatigue cracks can be characterized as mechanically small (comparable with the extent of local plasticity), microstructurally small (comparable with the scale of microstructure), physically small (typically less than 1 mm in size) or chemically small. Their common property is that they can propagate at rates which differ from, and generally exceed, those of long cracks at the same nominal stress intensity factor, leading to potentially non-conservative damage-tolerant lifetime predictions.

(2) The primary factors responsible for differences in behavior between long and mechanically and physically small cracks are, respectively, extensive plasticity ahead of the tip and crack tip shielding from crack closure behind the tip. Such differences may be in part normalized through characterization in terms of ΔK_{eff} or an equivalent elastic-plastic field parameter.

(3) The behavior of microstructurally small flaws differs from long cracks because of several factors, including excess crack tip plasticity, crack closure, crack shape and deflection, retardation at grain boundaries, and enhanced crack tip plastic strains. Such flaws may not be amenable to characterization in terms of a global field parameter, as their dimensions lie below continuum size scales.

(4) Approaches to apply small-crack methodology to fatigue life prediction are suggested in terms of (i) the use of ΔK_{eff}, or an equivalent elastic-plastic parameter, to extend damage-tolerant procedures into the physically small-crack regime and (ii) probabilistic analyses of the initiation and early growth of microstructurally small flaws.

(5) In life prediction, the concern is with predicting the growth of the most rapidly growing, ultimately fatal small crack. To design alloys which are resistant to such behavior, the approach must be to eliminate such maverick flaws, by creating microstructures to arrest the microstructurally small cracks which are able to nucleate. Thus, for optimum fatigue resistance, the approach may involve using clean materials to inhibit crack initiation, utilizing small, randomly oriented grains to inhibit small crack growth and employing crack tip shielding (*i.e.* microstructural "crack stoppers") to impede the growth of long cracks.

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