Small Fatigue Cracks

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Preface

This book represents the proceedings of the Second Engineering Foundation International Conference/Workshop on "Small Fatigue Cracks", held in the Hotel Miramar, Santa Barbara, California, during the week of January 5-10, 1986. The conference was organized by R. O. Ritchie (University of California, Berkeley) and J. Lankford (Southwest Research Institute), acting as conference co-chairmen, with help from D. L. Davidson (Southwest Research Institute), M. E. Fine (Northwestern University), R. P. Gangloff (University of Virginia), J. C. Newman, Jr. (NASA Langley), B. Tomkins (United Kingdom Atomic Energy Authority), and S. Suresh (Brown University), acting as session organizers. The meeting was the second in a series, beginning in January 1980 with the Asilomar conference on "Small Cracks", organized by M. E. Fine and R. O. Ritchie.

The problem of "small cracks" was first brought to the attention of the scientific community just over a decade ago, when Pearson published his now familiar paper (**Eng. Fract. Mech.**, 1975, vol. 7, p. 235) in which it was shown that the linear elastic stress intensity range (ΔK) failed to correlate the rates of growth of very small (0.006 to 0.5 mm) and large fatigue cracks in an aluminum alloy. In particular, the alarming observation was that the large through-crack results, measured on conventional-sized test specimens, were extremely non-conservative, as the small cracks grew much faster than large cracks at the same nominal "driving force", e.g., at nominally equivalent ΔK levels. A limited amount of essentially corroborating work quickly followed, and provided the focal point of the first conference at Asilomar. However, in the last five years, the small crack question has become of major importance in the fatigue community, and the literature has witnessed a corresponding large increase in papers devoted to the topic. The subject remains a critical area as it represents a regime where there is a possible "breakdown" in fracture mechanics analyses, yet at the same time it provides a link between classical stress/strain-life (S-N) and damage-tolerant methodologies. Moreover, the topic is of importance in many life prediction applications, since the time spent when the crack is small invariably accounts for the large majority of component lifetime.

In this proceedings, a state-of-art review is given by leading experts of the many facets of the small crack problem, including the questions of definition, crack initiation, modeling, microstructural and environmental effects, "crack driving force", and service applications. The book will be of use to students and practicing engineers alike in the fields of materials science and mechanical engineering.

Sponsorship for this conference was provided by the Engineering Foundation with additional financial support from the Air Force of Scientific Research, the Army Research Office, the National Science Foundation, and the Office of Naval Research. The editors would like to thank these agencies and the many individuals who helped to ensure that the conference, and hence these proceedings, was a success. In particular, thanks are due to Dr. Harold Comerer of the Engineering Foundation for making the meeting a reality, Drs. B. MacDonald (ONR), G. Mayer (ARO), A. H. Rosenstein (AFOSR), and R. Strang and M. Wuttig (NSF) for their financial support, the referees of the manuscripts for ensuring the quality of this book, Drs. R. J. Bucci, D. L. Davidson, M. E. Fine, R. P. Gangloff, J. C. Newman, S. Suresh, and B. Tomkins for acting as session chairmen, Ms. Donna Romano McArdle for her sterling efforts as conference secretary, and Ms. Madeleine Penton and Rosenda Fontana for their secretarial help.

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OVERVIEW OF THE SMALL CRACK PROBLEM

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In providing a technical overview for this meeting, it is perhaps important to ask how far the understanding of the behavior of small cracks, and related topics, has progressed since the first of the Engineering Foundation conference workshops on Small Fatigue Cracks, which was held in Asilomar, California in January 1980. Clearly, the definition of the many mechanisms of crack closure and their role in the development of a threshold for long cracks is now well established. Furthermore, on the basis of the presentations at this meeting, there are now far more results available on the related growth behavior of small cracks, although compared to long crack data the total number of papers reporting new information on small flaws is still not large. Similarly, although several models have been developed to describe small crack behavior, the total number of models is still relatively small. However, very significant progress has been made in the past six years in the sharper definition of critical issues, and in the fact that small crack methodology has begun to be appreciated in technological design and lifetime prediction, as evidenced by use of small crack data in the U.K. for turbine blade applications. Described below are our impressions of the highlights of this progress.

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. 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. At low growth rates, 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. 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 sub-threshold extension of small flaws can lead to potentially dangerous over-predictions of life.

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 flaws and (two-dimensional) short flaws, the latter being small in all but one dimension, clearly is of importance. Short flaws are through-thickness cracks, generally no smaller than 50 µm, which are created artifically 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, corrected by considerations of crack closure. Naturally-occurring small flaws, conversely, often approach microstructural dimensions, and although their behavior is still largely affected by closure, several other factors, including crack shape, enhanced crack tip plastic strains, and local arrest at grain boundaries, are of comparable significance.

Useful qualifiers remain microstructurally-, mechanically- and physically-small (or short), which pertain respectively to cracks small compared to microstructural dimensions, to the scale of local plasticity, and simply to cracks of a size less than 0.5 to 1 mm. In addition, fatigue cracks have also been described, with reference to environmental effects, as chemically-small, as described below. Each of these classes of small flaw is associated with particular phenomena which primarily distinguish it from long crack behavior (Table I). For example, for mechanically-small flaws, characterization in terms of elastic-plastic fracture mechanics (e.g., through the use of ΔCTOD or ΔJ) may help resolve differences in growth rates behavior between long and small cracks. On the other hand, for physically-small flaws, allowance for differences in the magnitude of crack closure (e.g., through the use of ΔK_{eff}) appears to be the predominant correlating factor. In the case of microstructurally-small flaws, all these factors may be important, plus others associated with local inhomogenities in the microstructure, non-uniform growth, retardation at grain boundaries, and so forth.

In particular, the microstructurally-small, rapidly growing crack corresponds to a three-dimensional crack whose plastic zone is less than the grain size. Thus, 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 thought to be a major factor in

Table I. 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 CTOD
Microstructurally-small	$a \lesssim d_g$[b] $2c \lesssim 5\text{-}10\ d_g$	crack tip shielding enhanced $\Delta\varepsilon_p$ crack shape	probabilistic approach
Physically-small	$a \lesssim 1$ mm	crack tip shielding (crack closure)	use of ΔK_{eff}
Chemically-small	up to ~ 10 mm[c]	local crack tip environment	

[a] r_y is plastic zone size or plastic field of notch

[b] d_g is 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

distinguishing small cracks from short through-thickness cracks, whose fronts must necessarily sample many grains. It further provides an explanation why crack tip shielding alone is generally sufficient to rationalize behavior of the short through crack.

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 I). Of particular significance is the varying contribution of crack tip shielding, with size of the crack wake, in locally reducing the effective driving force experienced at the tip. Such shielding arises in fatigue from crack closure, and to a lesser extent from crack deflection, and has been shown to be diminished at small crack sizes. However, for microstructurally-small cracks, it is now apparent that closure does not provide the entire solution (although uncertainities in experimental measurement make this question difficult to resolve). There is now considerable evidence that, additionally, such flaws are impeded locally by grain boundaries, influenced by non-uniform growth, and may experience higher cyclic plastic strains at their tips. Finally, differences in local crack tip environment with crack size provide the source of the chemically-short crack effect, as described below.

Environmental Effects

One of the most complex issues involved in the small crack problem is associated with (liquid) environmental effects. As noted by Wei, 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 upwards of $\sim$10 mm. (Precise definition of the size range for chemically-short cracks depends upon 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. 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.

"Driving Force" for Small Crack Propagation

Several workers have sought improved field characterizing parameters to describe the driving force for small crack advance (Table I). Although parameters such as $\Delta\sigma$ and $\Delta\varepsilon_p$ have been suggested, only those parameters that can be measured globally, yet define (at least nominally) local conditions, are considered relevant 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 and ΔS (the strain energy density). While certainly appropriate for taking account of excessive plasticity **ahead** of the tip, it should be noted that J is a nonlinear elastic parameter, and thus cannot similarly account for the vital influence of wake plasticity (prior plastic) zones **behind** the tip. 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 and cracks emanating from notches. 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. Here a probabilistic approach may be the optimum treatment to describe the behavior of such tiny flaws.

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. Similarly, intrinsic thresholds may exist for physically- and mechanically-short cracks, of magnitude comparable with the effective long crack value. For microstructurally-small cracks, however, the question of an intrinsic threshold may not be meaningful. Here the "fatal" flaws are the ones 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 light of evidence 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.

Small Crack Methodology in Life Prediction and Design

For physically- or mechanically-small cracks, the adoption of small crack methodology in life prediction analyses would appear 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.

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. 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, 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).

In essence, the ideal alloy design approach is to clean-up the material for optimum resistance to crack initiation, 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.

Summary

The essential features of the problems outlined here are treated in detail in the papers in this volume. We trust that this overview and the proceedings in general will provide a comprehensive, state-of-art survey of the many aspects of the small fatigue crack problem, which will be of use to the student, academic and practicing engineer alike.

Crack Initiation and Stage I Growth