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ANALYSIS OF SMALL CRACK BEHAVIOR FOR AIRFRAME APPLICATIONS

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ABSTRACT

The small fatigue crack problem is critically reviewed from the perspective of airframe applications. Different types of small cracks—microstructural, mechanical, and chemical—are carefully defined and relevant mechanisms identified. Appropriate analysis techniques, including both rigorous scientific and practical engineering treatments, are briefly described. Important materials data issues are addressed, including increased scatter in small crack data and recommended small crack test methods. Key problems requiring further study are highlighted.

INTRODUCTION

"Small" fatigue cracks are sometimes observed to grow faster than traditional "large" cracks at the same nominal value of the cyclic crack driving force, ΔK. Small cracks have also been observed to grow at non-negligible rates when the nominal applied ΔK is less than the threshold value, ΔK_{th}, determined from traditional large crack test methods. These phenomena imply that a structural life assessment based on large crack analysis methods can be nonconservative if the life is dominated by small crack growth.

Although the earliest documentation of the small crack effect was motivated by aircraft applications [1], small cracks have historically not been an important issue for most airframe structures. Classic damage tolerance analysis (DTA) typically mandates an initial flaw size beyond the small flaw regime, and other structural integrity assessments based on safe-life logic neglect explicit fatigue crack growth (FCG) arguments altogether.

However, ongoing developments in the airframe industry appear to be increasing the significance of small cracks for fracture control of aircraft structures. It is now recognized that multiple small flaws associated with multiple-site damage (MSD) can degrade residual strength capability in aging aircraft [2, 3]. In response to this observation, the Industry Committee on Widespread Fatigue Damage (WFD) of the Airworthiness Assurance Working Group (AAWG) has recently identified small cracks as a critical issue requiring further focused research [4]. In applications where durability analyses are employed, the equivalent initial flaw size (EIFS) which is back-calculated from some economic total life is often well within the small flaw regime [5]. Ongoing improvements in nondestructive evaluation (NDE) capabilities may lead to the re-definition of initial flaw sizes for traditional DTA which are down in the small flaw regime. And in some applications, structural integrity assessments formerly based on safe-life calculations now must be performed with DTA logic. The relevant crack sizes for these applications, however, are often much smaller than those historically associated with the DTA method.

The purpose of this paper is to provide a critical overview of the small crack problem in the context of airframe applications. Different types of small cracks are carefully defined and relevant mechanisms identified. Appropriate analysis techniques, including both rigorous scientific and practical engineering treatments, are briefly described. Important materials data issues are addressed, including increased scatter in small crack data and recommended small crack test methods. Key problems requiring further study are highlighted. Although this paper does provide an expert review of the small crack problem, it is not intended to be an exhaustively complete summary of all important research in the field. Many researchers have contributed to the level of understanding outlined in this paper, and it is not possible or attempted to acknowledge all of them individually.

DIFFERENT TYPES OF SMALL CRACKS

All small cracks are not the same. Different mechanisms are responsible for different types of "small crack" effects in different settings. Criteria which properly characterize small crack behavior in one situation may be entirely inappropriate in another situation. It is critical, therefore, to understand the different types of small cracks before selecting suitable analytical treatments. This review will consider three different types of small cracks: microstructurally-small, mechanically-small, and chemically-small.

Before beginning, one note on nomenclature is needed. The terms "small crack" and "short crack" both appear in the literature, and sometimes the two appear to be used interchangeably. In recent years, however, the two terms have acquired distinct meanings among many researchers. In the US research community, the currently accepted definition for a "small" crack requires that all physical dimensions (in particular, both the length and depth of a surface crack) are small in comparison to the relevant length scale. In contrast, a crack is defined as being "short" when only one physical dimension (typically, the length of a through-crack) is small in comparison to the length scale. These definitions are illustrated in Figure 1. However, it should be noted that this distinction has not always been observed in the literature, and that some current authors (esp. in Europe) choose to employ the terms with nearly reverse meanings. Whatever the usage, the reader should carefully observe which type of "little" crack is present in a given application. Some of the different implications of short vs. small cracks are discussed later in the paper.

Microstructurally-Small Cracks

A crack is generally considered to be microstructurally-small when all crack dimensions are small in comparison to characteristic microstructural dimensions. The relevant microstructural feature which defines this scaling may change from material to material, but the most common microstructural scale is the grain size. The small crack and its crack tip plastic zone may be embedded completely within a single grain, or the crack size may be on the order of a few grain diameters.

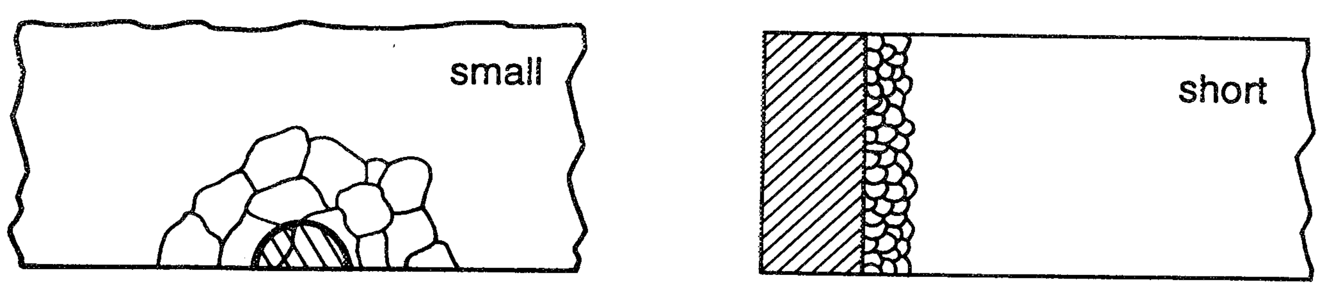

Figure 1. Schematic of "small" and "short" cracks, including relationship to microstructure.

Typical crack growth data for microstructurally-small cracks are shown for a 7075 aluminum alloy in Figure 2, along with traditional large crack data for the same material [6]. Note that small crack growth can occur at nominal ΔK values below the large crack threshold. Small crack growth rates are often faster than would be predicted by the large crack Paris equation (the dashed line in Figure 2), and the apparent Paris slope for the small crack data can be smaller than for the large crack data. Crack arrest (momentary or permanent) can occur at these low ΔK values, and this arrest is often observed to occur when the crack size, a, is on the order of the grain size, GS (i.e., when the crack tip encounters a grain boundary). However, not all small cracks arrest or even slow down at these microstructural barriers. As the crack continues to grow, the small crack da/dN data often merge with large crack data.

Why do microstructurally-small cracks behave this way? Several factors are involved, all related to the loss of microstructural and mechanical similitude. When the crack-tip cyclic plastic zone size, r_p^c, (and sometimes the crack itself) is embedded within the predominant microstructural unit (e.g., a single grain), the crack-tip plastic strain range is determined by the properties of individual grains and not by the continuum aggregate. The growth rate acceleration of small cracks embedded within a single surface grain is primarily due to enhancement of the local plastic strain range resulting from a lower yield stress for optimum slip in the surface grains [7, 8, 9]. This microplastic behavior also causes (and, in turn, is affected by) changes in crack closure behavior [10].

As a small crack approaches a grain boundary, the fatigue crack may accelerate, decelerate, or even arrest, depending on whether or not slip propagates into the contiguous grain [7]. The transmission of slip across a grain boundary in turn depends on the grain orientation, the activities of secondary and cross slip, and the planarity of slip. The transition of the small crack from one grain to another may require a change in the crack path, which may also influence crack closure. The resulting crack growth behavior is therefore very sensitive to the crystallographic orientation and properties of individual grains located within the cyclic plastic zone. As the crack grows, the number of grains interrogated by the crack-tip plastic zone increases and the statistically-averaged material properties become smoother.

However, it is important to note that the fundamental mechanism of crack growth is the same for small and large cracks in the near-threshold regime. In both cases, FCG occurs as an intermittent process involving strain range accumulation and incremental crack extension, followed by a waiting period during which plastic strain range reaccumulates at the crack tip [11]. Fatigue striations of equivalent spacing have been observed on the fracture surfaces of both large and small fatigue cracks tested under equivalent nominal ΔK ranges, as shown in Figure 2 for 7075 Al [11]. The essential difference between large and small cracks is that the number of fatigue cycles per identical striation is less for small cracks, due to differences in the local crack driving force.

How can the behavior of microstructurally-small cracks be modeled/predicted analytically? Several different approaches have been developed, ranging from detailed scientific models to simplified engineering treatments. At one extreme, complex micromechanical models attempt to address directly the changes in the local crack driving force. For example, a model derived by Chan and illustrated in Figure 3 incorporates microplastic grains ahead of a Barenblatt-Dugdale crack [7]. The nominal ΔK is modified by influence functions which explicitly describe the effects of microplastic/macroplastic yield strength, large scale yielding at the crack tip, and crack closure.

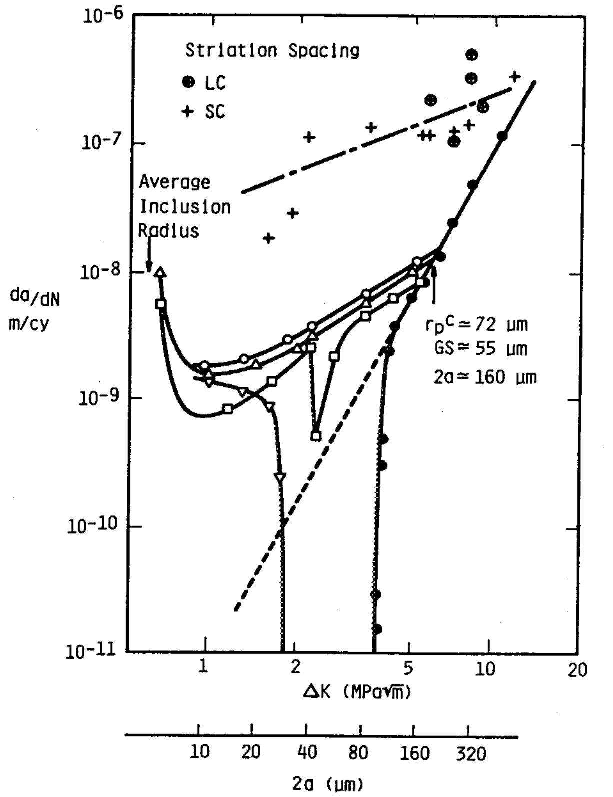

Figure 2. FCG data for 7075 Al, comparing crack growth rates and striation spacings for large cracks and microstructurally-small cracks.

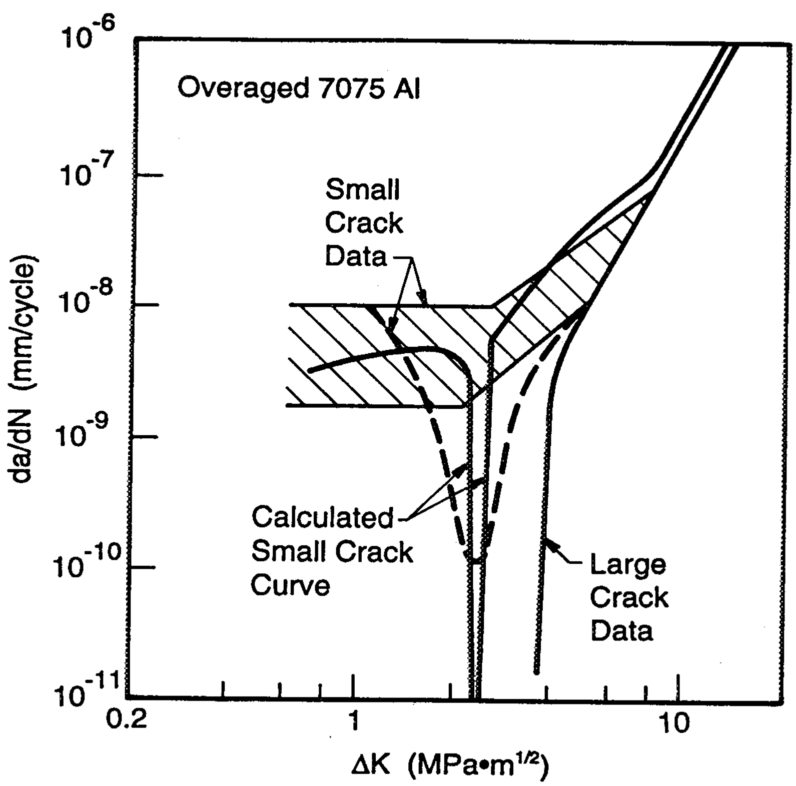

Figure 3. Predictions of a micromechanical model for microstructurally-small cracks.

Detailed experimental measurements of near-tip strains and displacements have suggested a general phenomenological model for microstructurally-small cracks which has been successfully applied to both engine disc and airframe alloys [12, 13]. Small crack growth rates were satisfactorily correlated with large crack data using a parameter $\Delta K_{eq} = (E\,\Delta J)^{1/2} = (E\,\Delta\sigma\,\delta_r)^{1/2}$, where the crack tip stress range $\Delta\sigma$ was calculated from the measured crack-tip strain range and δ_r is the cyclic crack-tip opening displacement. The parameter ΔK_{eq} was found to be simply related to the applied ΔK according to the expression $\Delta K_{eq} = \Delta K_p + U\Delta K$, where ΔK_p characterizes the plastic contribution to the crack driving force for small cracks and U is the effective stress range ratio which characterizes crack closure: $U = \Delta K_{eff}/\Delta K$. See Figure 4. Note that crack closure alone was not able to correlate the small crack data.

Simpler mechanical treatments have also been proposed to address FCG behavior in the microstructurally-small crack regime. The attractive simplicity of these models is that they avoid dealing directly with complex microstructural issues. Small crack acceleration effects are incorporated through simple modifications to mechanical parameters in the expression for the crack driving force. One such approach is that of El Haddad et al. [14], who replaced the actual crack length a by an effective length $a + a_0$ in order to calculate ΔK. This enhances the predicted crack growth rate when a is very small. A much more sophisticated approach has been developed by Newman [15]. The Newman model is based on computed changes in plasticity-induced crack closure for small cracks growing out of initiation sites simulated as micronotches. Newman has shown reasonably good success in predicting small crack growth rates and total fatigue lives for several different materials, including airframe alloys. These practical successes are encouraging, but it should be remembered that the simple mechanical treatments do not address the most fundamental causes of the microstructurally-small crack effect. Hence, the generality of the models cannot be assured.

Two other types of approaches, summarized in Figure 5, may be useful for some engineering applications in which it is not possible or practical to address changes in the driving force explicitly. *Stochastic treatments* which acknowledge the inherent uncertainties associated with microstructurally-small crack growth could address this uncertainty through appropriate statistical techniques. Formulation and calibration of these techniques would require extensive analysis of statistical-quality small crack data, which is a limitation. Variability of small-crack data is discussed further below. *Empirical engineering treatments* may be conservative bounding approaches which simply draw some upper bound to the crack growth data in the defined small-crack regime and use that bound as part of a total life computation, or fitting approaches which perform regression on small-crack data to generate a new set of Paris equation constants. These engineering treatments may be a useful means of avoiding detailed analysis, especially when small-crack data are available for materials and load histories representative of service conditions.

Based on these observations and models, several practical suggestions can be offered to predict growth rates for microstructurally-small cracks. In general, it appears that the large-crack Paris equation can be extrapolated downward at least to some microstructural limit. This limit is often estimated as about 5-10 grain diameters [16, 17, 18], or as the point at which the cyclic plastic zone size equals the grain size [16], although the actual limit is probably a more complex function of microplasticity and closure behavior [12]. The large-crack threshold should be neglected in this extrapolation. Some treatment of nominal plasticity and crack closure effects on the crack driving force (discussed at more length in the next section) is often useful to improve agreement with large crack data. However, it must be emphasized that some nonconservatism may remain if the true local microstructural effects have not been addressed. Guidance for addressing these effects can be obtained from various scientific approaches, although practical considerations may dictate the use of more general engineering approaches.

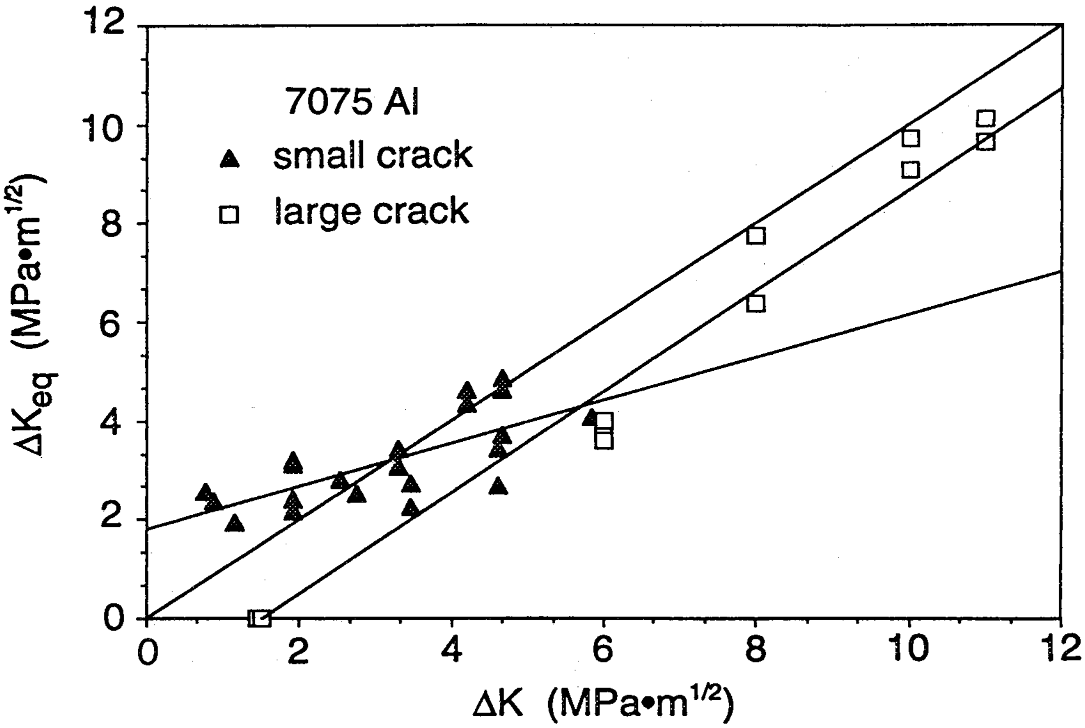

Figure 4. Comparison of ΔK_{eq} and nominal ΔK for large and small fatigue cracks in 7075 Al.

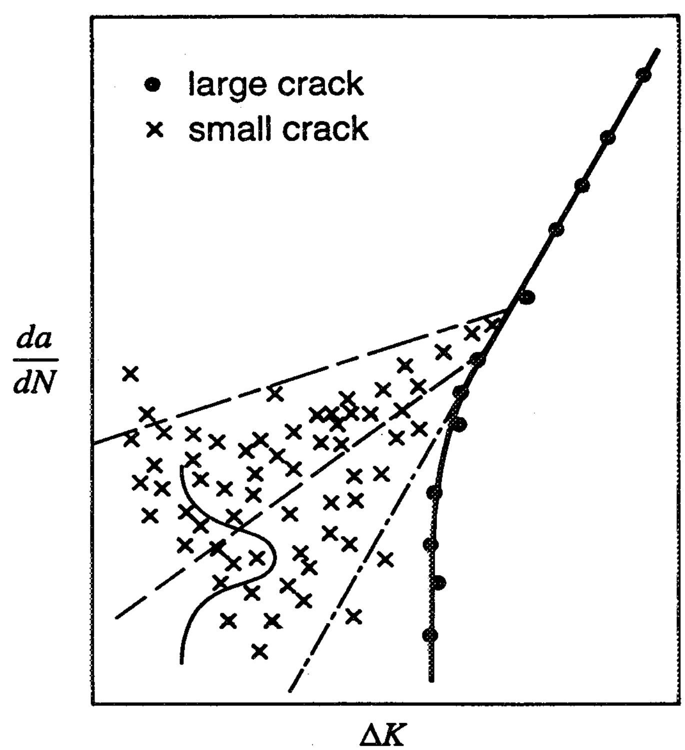

Figure 5. Schematic of potential stochastic and empirical engineering models for microstructurally-small crack growth.

Mechanically-Small Cracks

A crack is generally considered to be mechanically-small when all crack dimensions are small compared to characteristic mechanical dimensions. The relevant mechanical feature is typically a zone of plastic deformation, such as the crack tip plastic zone or a region of plasticity at the root of some mechanical discontinuity (e.g., a notch). The crack may be fully embedded in the plastic zone, or the plastic zone size may simply be a large fraction of the crack size, as illustrated by Figure 6. As discussed below, many microstructurally-small cracks are also mechanically-small, but our focus in this section is on mechanically-small cracks which are microstructurally-large. The "short" crack, as defined earlier, also behaves in the same manner as the mechanically-small crack. The crack front of a short crack interrogates many different grains and hence is not subject to strong microstructural effects.

Typical crack growth data for mechanically-small cracks are shown in Figure 7 for an HSLA steel [19]. Similar data are available for common airframe alloys [20]. Note again that small crack growth can occur below the large crack threshold. The slope of the Paris equation often appears to be roughly the same for small and large crack data, but the small crack data often fall above the large crack trend line when expressed in terms of nominal ΔK. Small or short cracks growing in notch fields often exhibit much faster growth than large cracks at comparable ΔK values, as shown in Figure 8 [21]. These small crack growth rates can actually decrease with increasing crack growth until they eventually merge with large crack data.

Why do mechanically-small cracks grow in this manner? The primary motivation appears to be that local stresses are significantly larger than those encountered under typical small-scale yielding (SSY) conditions, especially at near-threshold values of ΔK. These local stresses may have been elevated by the presence of a stress concentration, or they may simply be large nominal stresses in uniform geometries. These large local stresses significantly enhance crack-tip plasticity, which in turn enhances the crack driving force, either directly through violations of K-dominance, or indirectly through changes in plasticity-induced crack closure. The appropriate analytical treatment of the mechanically-small crack, then, primarily involves appropriate treatments of the elastic-plastic crack driving force and crack closure.

The nominal elastic formulation of ΔK, gradually becomes less accurate as a measure of the crack driving force as the applied stresses become a larger fraction of the yield stress. When σ_{max}/σ_{ys} exceeds about 0.7, a first-order plastic correction to ΔK may be useful. This correction may be based on the complete Dugdale formulation for the J-integral, expressed in terms of K [22, 23]. Alternatively, the correction can be based on an effective crack size defined as the sum of the actual crack size and the plastic zone radius [23, 24]. However, in most cases this first-order correction will change the magnitude of ΔK by no more than 10 to 20 percent. When the nominal plastic strain range becomes non-negligible (typically, when the total stress range approaches twice the cyclic yield strength), it will generally be necessary to replace ΔK entirely with some alternative parameter, such as a complete ΔJ formulation [24]. A comprehensive practical methodology for elastic-plastic FCG based on ΔJ is currently under development [25].

Plasticity-induced crack closure also becomes increasingly significant outside the small-scale yielding regime [24]. Normalized crack opening stresses are a function of normalized maximum stress, stress ratio, and stress state, and changes in closure behavior are most pronounced for large stresses, low stress ratios (R), and plane stress: typical conditions for mechanically-small cracks. Newman [26] has developed a simple closed-form equation based on a modified-Dugdale closure model of an infinite center-cracked plate which predicts normalized crack opening stress ($\sigma_{open}/\sigma_{max}$) as a function of $\sigma_{max}/\sigma_{flow}$, R, and constraint factor α. Recent finite element studies [27] have sug-

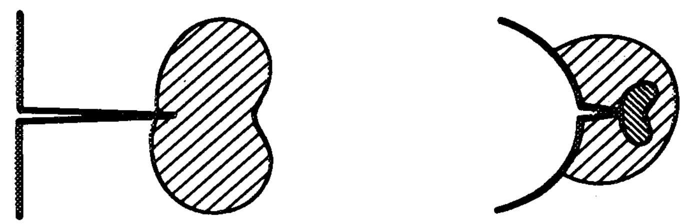

Figure 6. Schematic of relationship between mechanically-small cracks and plastic zones.

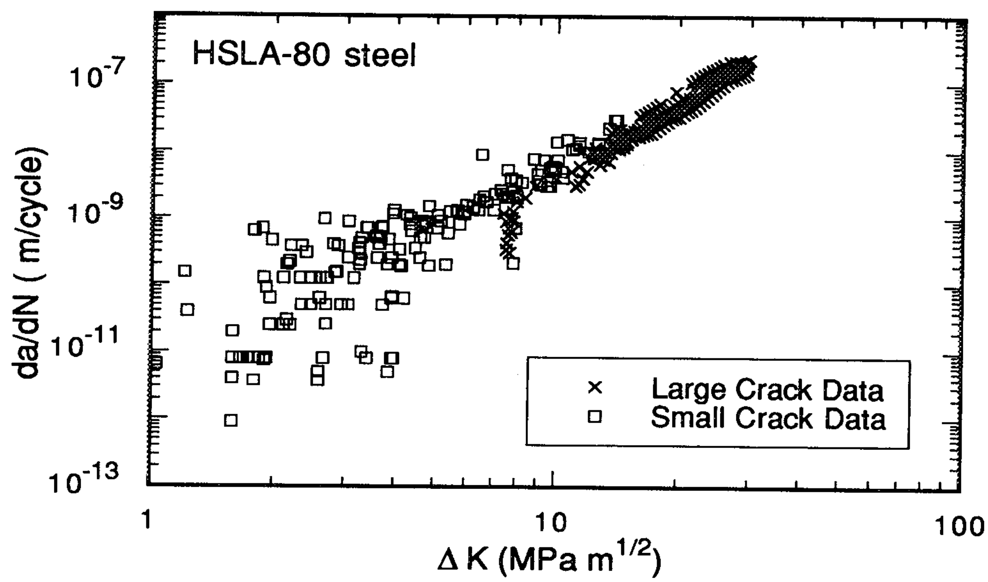

Figure 7. FCG data for large cracks and mechanically-small cracks in HSLA-80 steel.

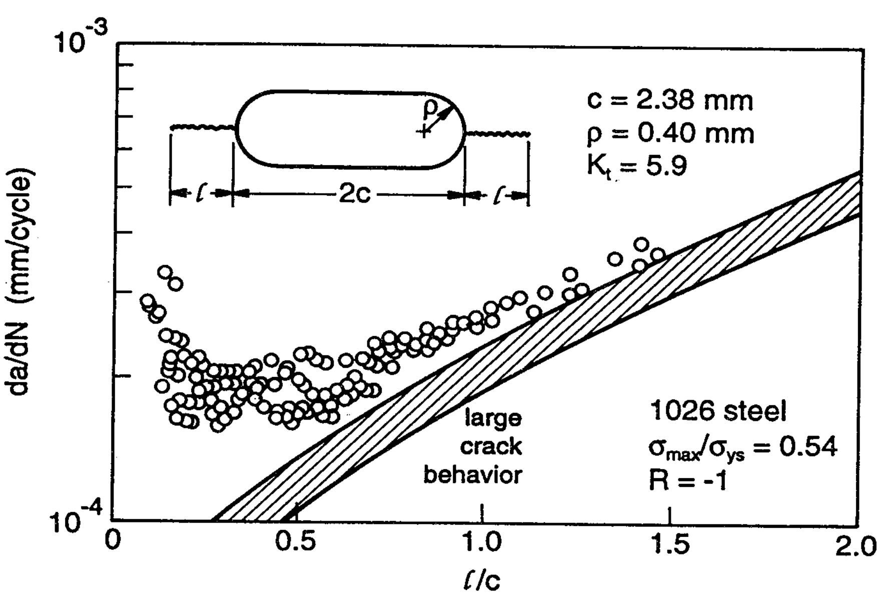

Figure 8. Typical FCG data for short cracks at notches.

gested that the Newman model may be extended satisfactorily to other geometries if $\sigma_{max}/\sigma_{flow}$ is replaced by K_{max}/K_0, where $K_0 = \sigma_{flow}(\pi a)^{1/2}$. The Newman equation and the finite element results are illustrated in Figure 9 for plane stress, $R = -1$. Changes in closure behavior are also significant for crack growth at notches, and simple models are available to predict these changes [21].

If appropriate revisions to the crack driving force based on plasticity and crack closure considerations are carried out, the growth rates of mechanically-small cracks can usually be predicted successfully by extrapolating the large-crack Paris equation and neglecting the large-crack threshold. This implies that if plastic corrections to ΔK are relatively minor, and if the closure behavior of the small crack does not differ significantly from the large cracks used to derive the Paris equation, that the small crack growth rates may be essentially the same as for the large cracks at the same nominal ΔK. It is not entirely clear under what conditions the large crack threshold will be observed by the small cracks, and in the absence of contradicting data, it is probably prudent to neglect the threshold for all mechanically-small cracks. If a complete crack closure analysis is not possible or practical, it may be sufficient to predict the growth rates of mechanically-small cracks using closure-free (high stress ratio) large crack data [28].

As noted earlier, the regimes of mechanically-small and microstructurally-small cracks can overlap. A more complete organizational scheme for large and small cracks from both microstructural and mechanical perspectives is given in Table 1 [29]. The "microstructurally-small" crack discussed earlier in this paper is often both microstructurally- and mechanically-small, although it is also possible to have a crack which is microstructurally-small and mechanically-large (cracks in single crystals, or cracks in very large grained materials). The traditional "mechanically-small" (or "short") crack discussed in this paper is typically microstructurally-large. Traditional large cracks are both microstructurally and mechanically large. The table also includes some suggestions for approximate size criteria based on comparisons of the crack size with either the crack-tip plastic zone size, r_p, or the microstructural unit size, M.

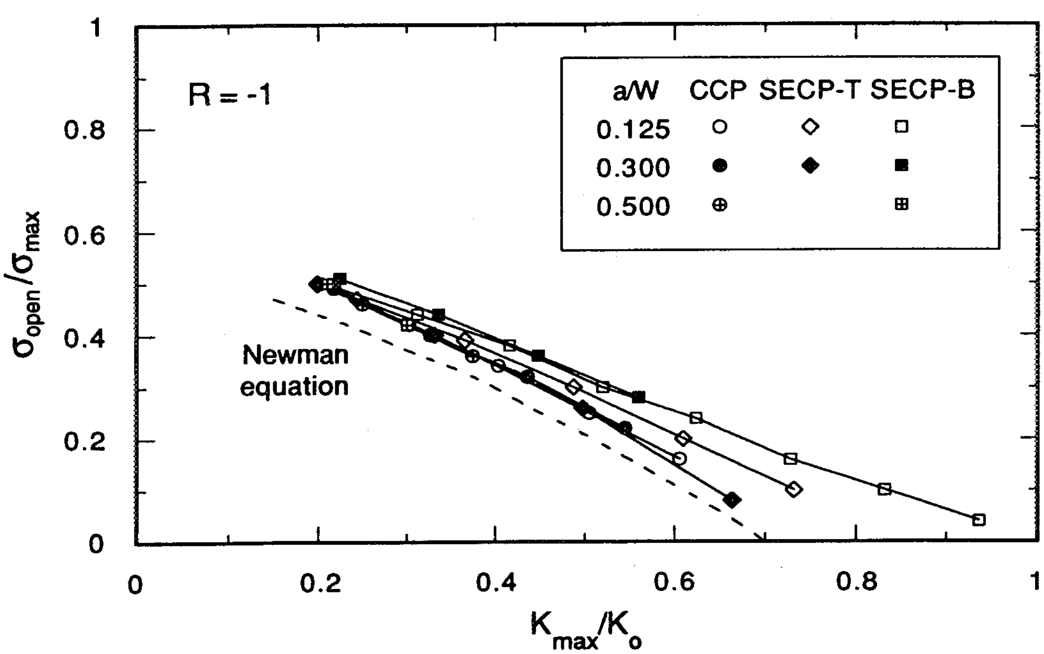

Figure 9. Normalized crack opening levels as a function of K_{max}/K_0, as predicted by FEM analyses and the Newman modified-Dugdale model.

Table 1. Classification of Crack Size According to Mechanical and Microstructural Influences

Mechanical Size / Micro-Structural Size	Large $a/r_p > 4\text{-}20$ (SSY)	Small $a/r_p > 4\text{-}20$ (ISY and LSY)
Large $a/M > 5\text{-}10$ ($r_p/M >> 1$)	Mechanically and Microstructurally Large (LEFM valid)	Mechanically Small/ Microstructurally Large (may need EPFM)
Small $a/M < 5\text{-}10$ ($r_p/M \sim 1$)	Mechanically Large/ Microstructurally Small (single crystal)	Mechanically and Microstructurally Small (inelastic, anisotropic, stochastic)

Chemically-Small Cracks

Experiments on a variety of ferritic and martensitic steels in aqueous chloride environments have shown that under corrosion-fatigue conditions, small cracks can also grow significantly faster than large cracks at comparable ΔK values [30, 31, 32]. This phenomenon is believed to result from the influence of crack size on the occluded chemistry which develops at the tip of fatigue cracks. The specific mechanism responsible for this "chemical crack size effect" is believed to be the enhanced production of embrittling hydrogen within small cracks resulting from a crack size dependence of one or more factors which control the evolution of the crack-tip environment—specifically, convective mixing, ionic diffusion, or surface electrochemical reactions [33, 34]. This mechanism is distinctly different from that responsible for the enhanced rate of crack growth in microstructurally- or mechanically-small fatigue cracks.

The chemical crack size effect is clearly illustrated by the data of Gangloff [31] for 4130 steel in an aqueous NaCl environment (see Figure 10). Note that corrosion-fatigue crack growth rates from small surface cracks (0.1 to 1 mm deep), as well as short through-thickness edge cracks (0.1 - 3 mm), are appreciably faster than corrosion-fatigue crack growth rates from large through-thickness cracks (25 - 40 mm) in standard compact tension specimens. It is also interesting to note that the corrosion-fatigue crack growth rates for small surface cracks decrease with increasing applied stress (at a given ΔK), and this trend is opposite to the dependence of applied stress on crack growth rates in small fatigue cracks. Moreover, all of the corrosion-fatigue crack growth rates in NaCl are enhanced compared to those in a moist laboratory air environment, even though the latter were generated with both small and large cracks. Thus, in relation to the fatigue small crack effect, the chemical small crack effect is of potentially greater importance since it can occur over a much larger range of crack sizes (up to 3 mm).

The chemical crack size effect in high strength steels is relevant to aircraft structural components such as landing gear. Do similar effects occur in high strength aluminum alloys used in airframes?

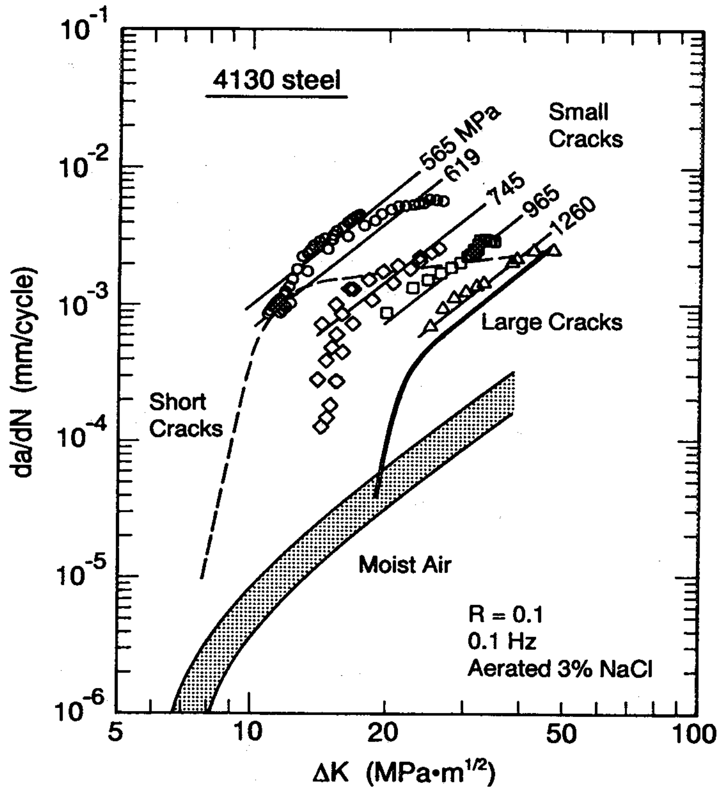

Figure 10. Corrosion-fatigue crack growth data for large and chemically-small cracks in 4130 steel [31].

Although data on the aluminum alloys is sparse at this point, preliminary data are available which enable an initial assessment of the problem. Data of Piascik and Gangloff [35] suggest the lack of a chemical crack size effect in both 2090 and 7075 aluminum alloys exposed to an aqueous chloride environment. Recent data from NASA-Langley [36] on 2024-T3 in a similar environment also support the lack of a chemical crack size effect, as shown in Figure 11. Thus, in contrast to steels, aluminum alloys may be immune from chemical crack size effects. Further studies are currently underway to address this question.

Several possible reasons for the apparent difference in the small crack behavior of steel and aluminum alloys can be hypothesized. First, it should be recognized that the data on steels and aluminum alloys have been generated under different environment and loading conditions. Specifically, the aluminum small crack data have been obtained under deaerated conditions and an electrode potential of -700 mV (versus the saturated calomel electrode, SCE), while the steel small crack data have generally been conducted under aerated conditions and, in the case of Ref. [31], an electrode potential of -550 mV SCE. In addition, most of the aluminum small crack data were obtained at high load ratios (R), particularly in the important low ΔK regime, while the steel small cracks were obtained at low load ratios. This difference in load ratios may be significant since it causes differences in the crack opening displacement. Analytical models for the evolution of the environment within cracks indicate that the ratio of crack surface area to occluded solution volume is a fundamental variable affecting the crack-tip environment [34].

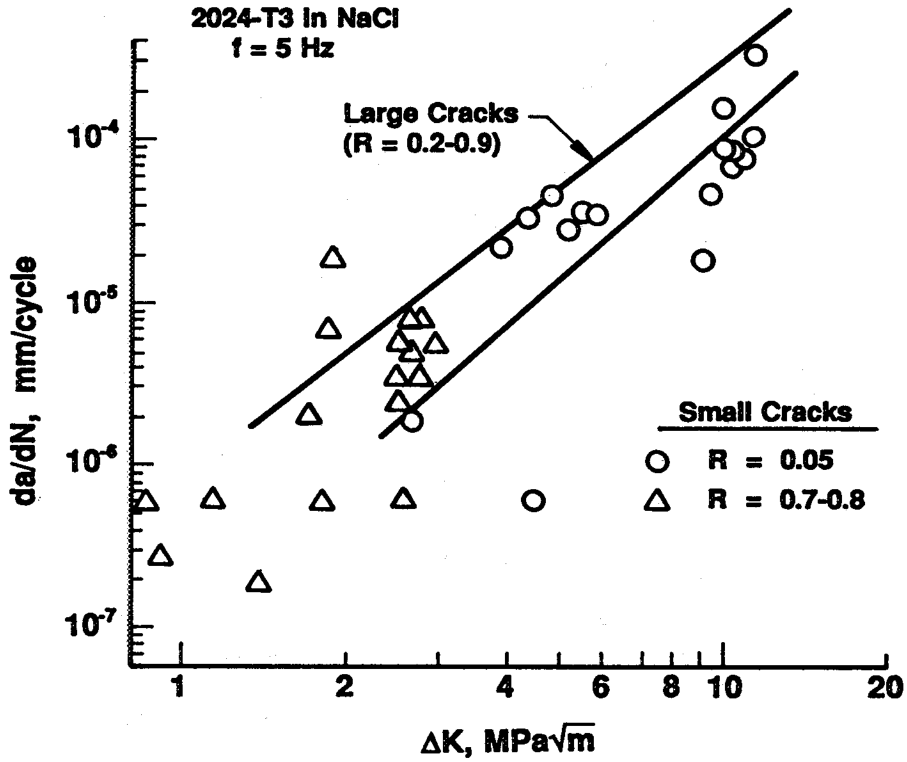

Figure 11. Corrosion-fatigue crack growth data for large and small cracks in 2024-T3 Al [36].

Second, the rate controlling process for environment-enhanced FCG may differ in steel and aluminum alloys. Crack growth rates in steels are controlled by electrochemical reactions on the freshly created metal at the crack tip [37]. Studies of aluminum alloys exposed to water vapor suggest that the surface reaction in the aluminum-water system is relatively fast, so that transport of water to the crack tip is the rate controlling process [38]. Unfortunately, specific results on the rate controlling process for aluminum alloys in liquid water are not yet available. Thus, an assessment of whether or not these fundamental differences in rate controlling processes account for the observed differences in chemical crack size effect in these two alloy systems must await further elucidation of the underlying kinetic mechanism(s).

MATERIALS DATA ISSUES

Scatter in Small Crack Data

Even when suitable analysis techniques are able to predict the central tendencies of small crack data, the life prediction task may still be difficult. The remaining problem is the large amount of scatter (sometimes several orders of magnitude) often observed in small crack growth rate data. This leads to greater uncertainty in life calculations, especially when the small crack regime dominates the total life. Analytical approaches based on simple upper bounds to the small crack regime, as suggested earlier, may be unacceptably overconservative in some applications.

At least three major sources of this apparent variability have been identified [19]. Some true variability is due to stochastic microstructural effects: local differences in grain orientation, micro-plastic yield strength, and grain boundary effects, which may become especially significant when the crack driving force is small. On the other hand, some apparent variability is actually only an artifact of measurement error. These errors become significant when the crack growth increment becomes small relative to the measurement resolution. Finally, some apparent variability can be attributed to mathematical averaging effects. The normal point-to-point variability is effectively averaged out for most large cracks, when the crack travels a long distance during the measurement interval. Since the small crack travels only a short distance during the measurement interval, this normal variability becomes more evident (as it would be if large cracks were measured at much shorter intervals).

The appropriate treatment for small crack scatter depends, at least in part, on the origin of the scatter. Some scatter which is only apparent can be effectively reduced with improvements in the analytical schemes used to process the raw crack growth data, including data filtering and modified incremental polynomial techniques [39]. However, other forms of scatter may require a formal stochastic treatment of the data. Many stochastic FCG models are available in the literature. Unfortunately, many of these models require extensive data of high statistical quality, which is often difficult (expensive) to obtain for small cracks. Other stochastic FCG models designed for practical engineering applications, such as the lognormal random variable (LRV) model, require fewer data and simpler calculations. However, these models are often not able to address the unique scatter associated with small cracks on a consistent basis with the reduced scatter associated with large cracks. New stochastic FCG models are currently being investigated to address these issues. Figure 12 compares a modified LRV model [19] with the standard LRV approach for the HSLA-80 steel data presented earlier.

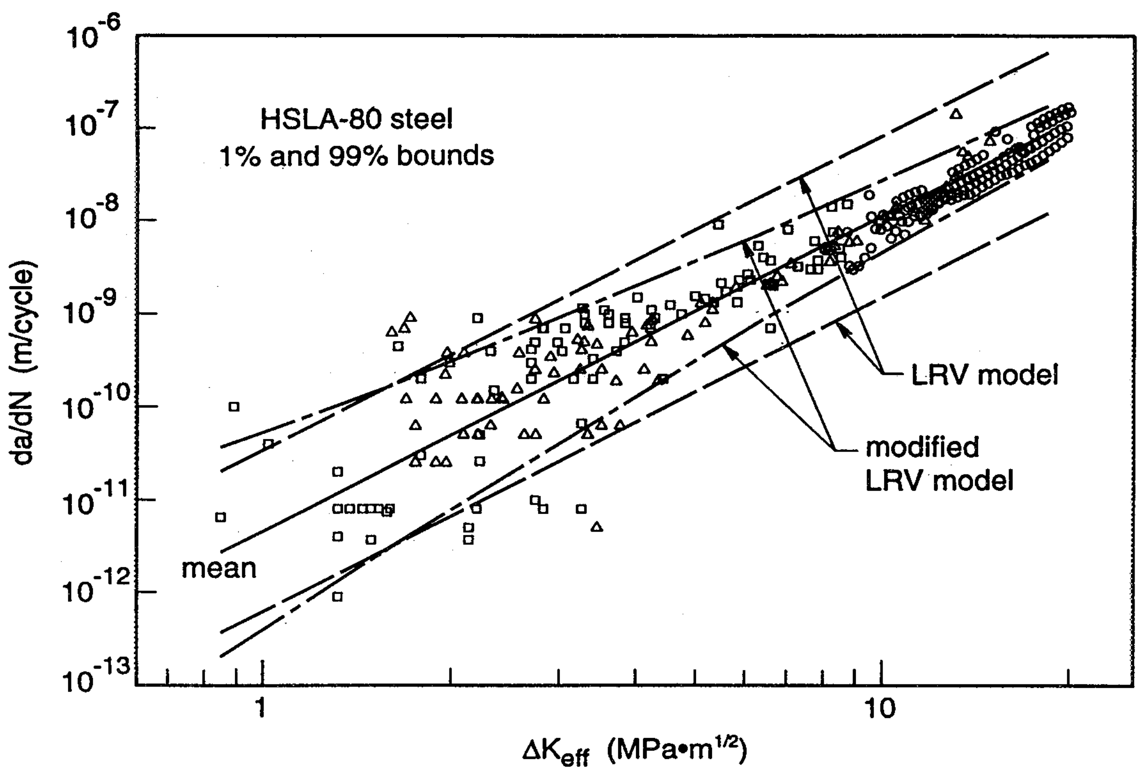

Figure 12. Stochastic treatments of large and small crack data for HSLA-80 steel, based on conventional and modified lognormal random variable models.

Small Crack Test Methods

Previous suggestions about practical engineering treatments of small cracks have usually attempted to derive predictions of small crack growth rates from commonly available large crack data. In some applications, however, this approach will not be adequate (e.g., for some microstructurally-small cracks), and in other applications the need may arise to obtain further experimental evidence for small crack behavior. Unfortunately, small crack growth rates cannot usually be measured with the standard procedures developed for large cracks, such as the current ASTM Test Method E 647 [40].

To address this dilemma, the Task Group on Small Fatigue Cracks within ASTM Committee E 8 on Fatigue and Fracture is currently attempting to develop an appendix to Test Method E 647 to provide guidelines for measuring the growth rates of small fatigue cracks. Since that document is currently undergoing the balloting process required to become an official ASTM standard and has not yet been formally approved, it is not prudent to provide specific details at this time. However, a few general remarks are appropriate.

Complete, detailed test procedures are not prescribed. Instead, the appendix provides general guidance on the selection of appropriate experimental and analytical techniques and identifies aspects of the testing process that are of particular importance when fatigue cracks are small. Several different crack length measurement techniques are permitted, and detailed descriptions of each are available in a recent ASTM STP [41]. Several different specimen geometries are suggested, including rectangular or cylindrical surface crack specimens, corner-crack specimens, and part-through cracks in edge-notched specimens. Special attention is given to issues such as surface preparation, crack initiation sites, and calculation of ΔK and da/dN.

DISCUSSION

The small crack problem is certainly a complex and multidimensional subject. Occasional confusion on the part of researchers about different types of small cracks and their appropriate experimental or analytical treatment has added further to the complexity of the literature. This short review paper, while attempting to better organize the complexity and point towards practical analytical solutions, has inevitably oversimplified some of the intricate details. But that is the inevitable limitation of nearly any practical engineering treatment of a complex technical problem. The goal is not to create universally precise theories, but rather to construct working engineering models which predict, to a first order, the key characteristics of the phenomena under consideration, based on fundamental understandings of the relevant scientific mechanisms.

Additional work is needed to develop further the analytical methods identified or proposed here. Some of these needs have been highlighted in the text: practical engineering methods to describe microstructurally-small crack growth at the subgrain size, clarification of the chemically-small crack effect (or lack thereof) in aluminum alloys, statistical treatments of small crack behavior, etc. Further verification testing and analysis is also required to confirm the applicability of these methods to common airframe alloys for characteristic geometries and load histories.

Some other unsolved problems have not yet been mentioned in this paper. One challenge of particular importance is variable amplitude loading. The great majority of previous small crack studies, including most of those referenced herein, have been limited to constant amplitude loading. Variable loading effects on small cracks are not well understood as a result, but available studies have suggested that variable amplitude loading can exacerbate the small crack effect [20, 42]. This may be due, at least in part, to changes in crack closure behavior for variable load histories outside the small-scale yielding regime [43], but other microstructural effects may also be significant. Other outstanding small crack issues include the proper treatment of crack dwell or crack arrest as an intrinsic feature of microstructurally-small crack growth, and the characterization of crack closure in practical airframe geometries such as fastener holes with residual stresses.

The practical relevance of small crack phenomena for engineering analysis of airframe structures has not yet been fully established. Further study of problems such as MSD in aging aircraft should provide helpful guidance. In those applications where the growth of small cracks must be considered, however, reliable analytical and experimental techniques are now available to perform many of the required computations of damage growth with reasonable confidence.

CONCLUSIONS

1. A proper identification of the *type* of small crack encountered is essential to choosing an appropriate analytical treatment.

2. Satisfactory scientific explanations for small crack behavior are now available, but some additional work is needed to develop satisfactory engineering treatments for all applications.

3. A practical engineering methodology for mechanically-small cracks includes extrapolation of the large-crack Paris equation, with appropriate attention to changes in crack closure and plasticity modifications to the crack driving force.

4. Practical engineering methodologies for microstructurally-small cracks are less complete. Available simple mechanics approaches may be useful, but will be inadequate in some applications. Micromechanics and phenomenological approaches provide valuable guidance, but ultimately statistical or simple bounding approaches may be required.

5. It is not entirely clear if aluminum alloys commonly used in airframe applications exhibit a significant chemically-small crack effect.

6. Small cracks often exhibit significantly greater scatter in growth rates than large cracks due to stochastic variations in the local microstructure, measurement error, and decreased mathematical averaging. Alternative analytical techniques may be required to address this variability.

7. Guidelines for small crack test methods are becoming available.

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