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Fatigue Crack Propagation in Aerospace Aluminum Alloys

Richard P. Gangloff*
University of Virginia, Charlottesville, Virginia 22903
and
Robert S. Piascik,† Dennis L. Dicus,‡ and James C. Newman Jr.†
NASA Langley Research Center, Hampton, Virginia 23665

This article reviews fracture mechanics-based, damage tolerant characterizations and predictions of fatigue crack growth in aerospace aluminum alloys. The results of laboratory experimentation and micromechanical modeling are summarized in the areas of 1) the wide range crack growth rate response of conventional aluminum alloys, 2) fatigue crack closure, 3) the fatigue behavior of advanced monolithic aluminum alloys and metal matrix composites, 4) the short crack problem, 5) environmental fatigue, and 6) variable amplitude loading. Uncertainties and necessary research are identified. This work provides a foundation for the development of fatigue resistant alloys and life prediction codes for new structural designs and extreme environments, as well as to counter the problem of aging components.

Introduction

THE fracture mechanics approach to controlling fatigue crack propagation (FCP) quantitatively couples laboratory studies on alloy performance and fatigue mechanisms with damage tolerant life prediction methods through the concept of growth rate similitude. This method, illustrated in Fig. 1, is traceable to the seminal results of Paris et al.[1] for the case of moist air environments, and is outlined in modern textbooks.[2,3] Subcritical FCP is measured in precracked laboratory specimens according to a standardized method.[4] Crack length a vs load cycles N data are acquired, usually with constant amplitude loading, and are analyzed to yield a material property; averaged fatigue crack growth rate da/dN as a function of the applied stress intensity range, ΔK. ΔK is the difference between maximum K_{max} and minimum K_{min} stress intensity values during a load cycle. Paris et al. experimentally demonstrated the principle of similitude; i.e., equal fatigue crack growth rates are produced for equal applied stress intensity ranges, independent of load, crack size, and component or specimen geometry.[1] Wei and Gangloff[5] extended this concept to describe corrosion fatigue crack propagation in aggressive gas and liquid environments.

The similitude principle enables an integration of laboratory $da/dN - \Delta K$ data to predict component fatigue behavior in terms of either applied stress range $\Delta\sigma$ vs total life N_f, or a vs N, for any initial defect size and component configuration. In addition to the laboratory data, these calculations require loading and stress analyses, initial crack size and shape, and a component stress intensity solution. This method has been developed for complex structural applications in the energy, petrochemical, and transportation sectors.[6–9] In these cases classical fatigue design rules, based on smooth specimen data and which do not generally account for time-dependent environmental damage, are being challenged by the fracture mechanics method.

Damage tolerant design requirements for aerospace structures stimulated the development of FCP life prediction methods based on fracture mechanics. In 1979 two round-robin programs were initiated in the U.S.[10] and Europe[11] to implement the approach illustrated in Fig. 1 for aerospace components and loading spectra. The methods and models used in these programs are categorized as either empirical (viz.,

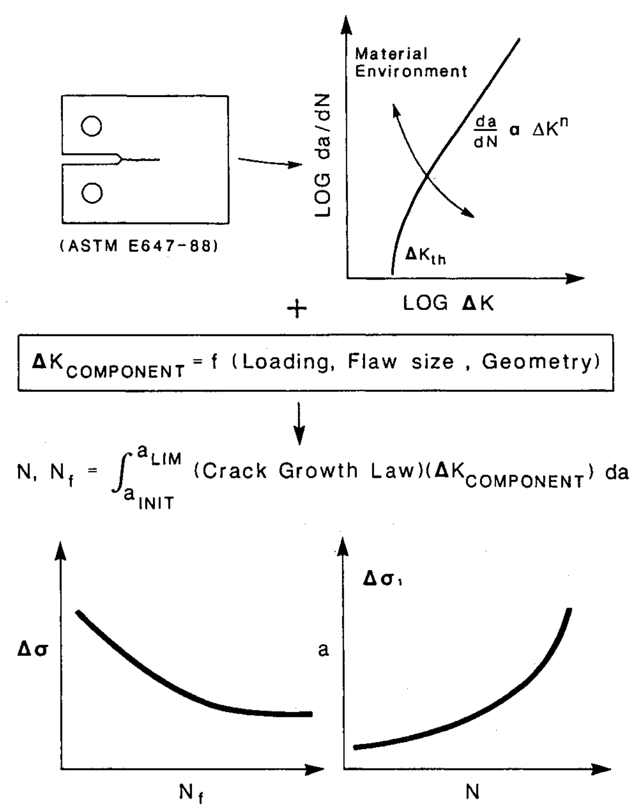

Fig. 1 Fracture mechanics approach to controlling fatigue crack growth, including laboratory material property characterization and component life prediction.

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*Professor, Department of Materials Science and Engineering, School of Engineering and Applied Science.

†Senior Scientist, Mechanics of Materials Branch, Materials Division.

‡Senior Scientist, Metallic Materials Branch, Materials Division.

yield zone or crack closure) or analytical crack closure models. Each modeled plasticity effects and most accounted for load-interaction effects such as crack growth retardation and acceleration for mission-relevant load spectra.

Empirical yield zone models were generally based on the Willenborg et al.[12] model, but modified for improved accuracy.[13,14] Yield zone models require several constants, other than constant amplitude FCP properties, to accurately predict crack growth under aircraft loading. Empirical crack closure models also require several empirical constants to account for variations in crack opening stresses during spectrum loading.[15,16] Analytical crack closure models predict the variation in crack opening stresses during a load history.[17] These models, coupled with the approach in Fig. 1, have been incorporated into fatigue damage tolerance computer codes for aerospace structures, including CRKGRO,[18] NASA FLAGRO,[19] NASCRAC,[20] and FASTRAN.[21]

Results from these studies indicate that advanced yield zone and crack closure-based models reasonably predict crack growth lives under aircraft spectrum loading, provided that the models are adjusted based on results from experiments with similar materials and loadings.[10,11] The studies demonstrate that the inclusion of crack growth retardation and acceleration is necessary to give accurate life results, and that crack closure is a significant concept for modeling fatigue crack growth.

Objective

The objective of this article is to review the state-of-the-art regarding fracture mechanics-based laboratory characterizations, damage mechanisms, and model predictions for fatigue crack growth life in aerospace aluminum alloys. Sections summarize research over the past 20 yr on 1) fatigue crack closure, 2) the wide range $da/dN - \Delta K$ response of aluminum alloys, 3) the fatigue behavior of new monolithic aluminum alloys and metal matrix composites, 4) the short crack problem, 5) environmental fatigue, and 6) variable amplitude loading.

Fatigue Crack Closure

The crack closure concept is an important development from fatigue crack propagation research.[22] While stress intensity similitude was initially based on applied ΔK, as indicated in Fig. 1, experiments and modeling demonstrate that crack surfaces can contact during the unloading portion of the fatigue cycle at positive applied stress levels. Such contact shields the crack tip from further unloading; the cyclic strain range at the crack tip is accordingly reduced from that level typical of the complete excursion of stress intensity from K_{min} to K_{max}. If operative, crack closure causes reductions in growth rates compared to the values typical of unhindered crack opening and closing at the same applied ΔK range.[23–27] Extrinsic crack growth is that which is closure-influenced, while fatigue under closure-free loading is said to be intrinsic.

The effective stress intensity range ΔK_{eff}, defined as the difference between K_{max} and $K_{opening}$, reasonably correlates da/dN similar to that indicated for applied ΔK in Fig. 1. $K_{opening}$ is the stress intensity level above which crack opening and cyclic crack tip strains are unaffected by surface closure contact, and equivalently, the K level below which a resolvable amount of crack surface contact occurs during loading or unloading. $K_{opening}$ is often referred to as $K_{closure}$; both are arbitrarily defined, and are experimentally measured or model predicted. The extent of crack closure depends on applied ΔK, stress ratio $R = K_{min}/K_{max}$, stress level, crack length, specimen thickness, alloy microstructure, and environment. Crack closure provides an explanation for the effects of a variety of metallurgical, mechanical, and environment chemistry variables on FCP.

All known mechanisms for crack surface contact during tensile fatigue loading act in the wake of the propagating crack.[26] Three specific shielding mechanisms are illustrated in Fig. 2. Plasticity induced closure, Fig. 2a, arises from interference between mating crack surfaces which were permanently deformed as the crack tip passed through the plastic zone. Plasticity induced closure is a dominant mechanism and was the first to be extensively studied in experiments and numerical analyses. This closure mechanism is particularly important for plane stress deformation, typical of higher ΔK levels. Little is known about the effect of plasticity induced closure on near-threshold FCP. Other forms of closure, such as roughness or oxide/corrosion product induced closure occur, but they have yet to be quantitatively modeled. Roughness induced closure, shown in Fig. 2b, arises from premature contact of crack surface asperities which may be pronounced for specific microstructure, deformation mode, and environment conditions. Roughness induced closure is significant at near-threshold stress intensities, where crack tip opening displacements are comparable to fracture surface asperity heights, and when mode II displacements exist. As a third mechanism for closure, FCP rates are reduced when crack surface corrosion products reach a thickness comparable to crack opening displacements, Fig. 2c. Here, the crack is wedged open at stress intensities above K_{min}, resulting in reduced crack tip damage.

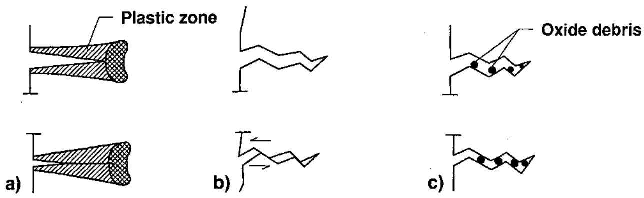

Fig. 2 Fatigue crack wake mechanisms for closure based on a) plasticity, b) surface roughness, and c) corrosion debris (after Ritchie[26]).

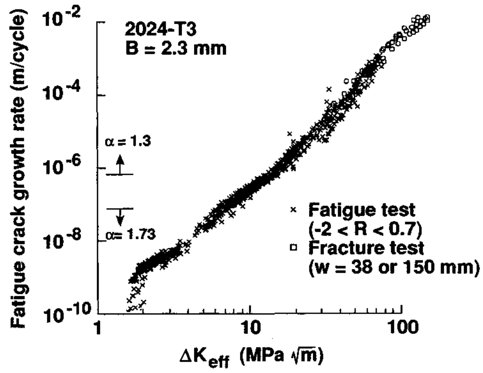

Fig. 3 Plastic zone corrected ΔK_{eff} correlation of da/dN for AA2024-T3 subjected to cyclic loading over a wide range of ΔK, R, and stress level.

Measurements of closure, or more correctly the load corresponding to $K_{opening}$, are typically based on compliance methods, and provide a means of approximating ΔK_{eff}. There are two problems with this approach. The resolution and reproducibility of opening load measurements from compliance changes, measured at various locations on a specimen, are uncertain and the target of an ongoing standardization effort within ASTM Committee E08.[28] Secondly, it is unlikely that crack tip cyclic strains vanish at and below a single opening load; rather, closure develops over a portion of the load cycle. Compliance measurements of closure cannot distinguish between the various mechanisms indicated in Fig. 2.

The crack closure concept has been extensively used to correlate FCP rate data under constant amplitude loading. In principle, such results provide intrinsic material property data for component fatigue life prediction. An example of FCP rate data for aluminum alloy (AA) 2024-T3 center crack tension panels is shown in Fig. 3. Symbols (x) indicate experimental results obtained from 2.3-mm-thick specimens loaded over a range of stress ratios ($-2 \leq R \leq 0.7$) and applied stresses ($\Delta S = S_{max} - S_{min}$; $10 \leq S_{max} \leq 280$ MPa).[29–31] The open symbols at high da/dN are obtained from monotonic fracture tests with stable crack extension treated as crack growth in a single load cycle.[32] Values of ΔK_{eff} were calculated from crack opening stress equations developed from a plasticity induced closure model.[32] This model requires a "constraint" factor α, which approximates the effect of triaxial constraint on yielding ahead of the crack tip. For plane stress α equals 1.0, and for plane strain α is 3.0. For a thin sheet of AA2024, α of 1.3 was selected for da/dN greater than 7.5×10^{-7} m/cycle (end of the transition from flat to slant crack growth), and α of 1.7 for rates less than 9×10^{-8} m/cycle (beginning of the transition from flat to slant crack growth). Crack growth on a 45-deg plane through the thickness indicates plane stress, while flat crack growth indicates nearly plane strain constraint. These values of α were selected to uniquely correlate da/dN vs ΔK_{eff} for the various R values.

For aluminum alloys, measurements and model calculations show that, even in the near-threshold regime, plasticity induced crack closure can occur over a large percentage of S_{max}.[17] For example, Fig. 4 shows measured (solid symbols)[31] and calculated (open symbols) threshold stress intensity range ΔK_{th} values for AA2024-T3 sheet as a function of R. (ΔK equals K_{max} for negative stress ratios.) The closure model analysis assumed that the effective ΔK_{th} was 1.65 MPa$\sqrt{m}$. A 6% load shedding method was used in the experiments, while two analysis methods were used: 1) an incremental smooth and 2) the 6% method.[32] These results show that the increase in ΔK_{th} with decreasing R from near 1.0 can be calculated from a plasticity induced closure model.

The plasticity induced closure model, applied to analyze roughness or corrosion debris induced closure, demonstrated the effectiveness of these shielding mechanisms. Figure 5 shows that an interference particle on the crack surface affects the crack opening stress S_{op}. The particle was arbitrarily chosen as a two-dimensional rectangle (10 μm by 20 μm by thickness), located at a distance d from the crack tip. The dashed line shows steady-state results for constant amplitude loading ($S_{max}/\sigma_0 = 0.02$, where σ_0 is flow stress), and a constraint factor α of 1.7 (the Irwin plane strain condition). A particle located 10 mm from the crack tip had no effect on S_{op}. As the particle was placed closer to the crack tip, however, complex closure behavior was revealed. After an initial decrease in S_{op} for a particle between 10 and 1 mm behind the crack tip, a steady rise in S_{op} was observed for d less than 1 mm. These results suggest that the interference must be close to the crack tip to influence S_{op} and to enhance crack tip shielding by closure.

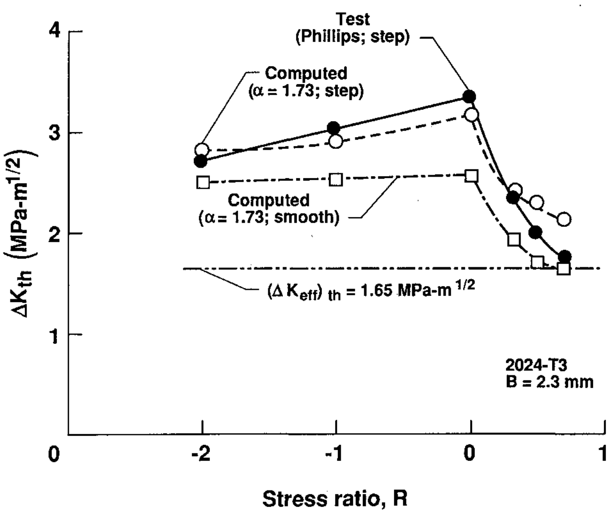

Fig. 4 Comparison of experimental and model predicted fatigue crack growth thresholds for AA2024 as a function of stress ratio.

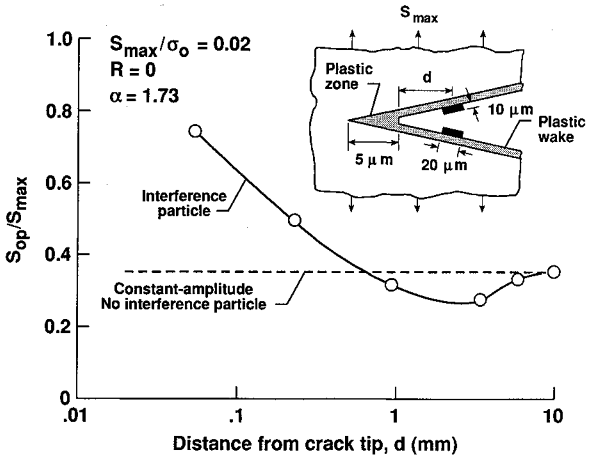

Fig. 5 Influence of an interfering particle on crack opening stress under constant amplitude fatigue loading for an aluminum alloy.

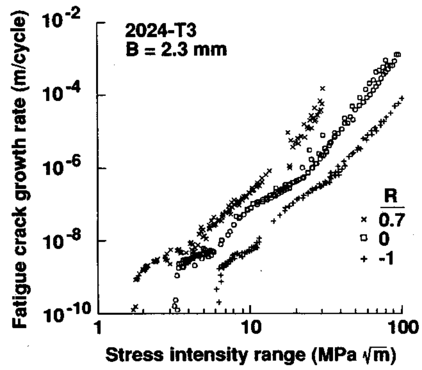

Fig. 6 Fatigue crack growth kinetics for AA2024 in moist air and over a wide range of ΔK, at R of −1, 0, and 0.7.

Fatigue Crack Propagation Data Bases: Aluminum Alloys

Conventional Aluminum Alloys

The fatigue crack propagation behavior of aerospace aluminum alloys, stressed in vacuum, is generally approximated by empirical relationships developed by Speidel[33]

$$\frac{da}{dN} = 1.7 \times 10^{6}(\Delta K/E)^{3.5} \qquad (1)$$

$$\Delta K_{th} = 2.7 \times 10^{-5}E \qquad (2)$$

where da/dN is in units of m/cycle, ΔK and ΔK_{th} are in MPa$\sqrt{m}$, and the modulus of elasticity E is in MPa. These results should only be employed as a guideline, and may not describe the behavior of novel alloy microstructures, crack closure dominant situations, short crack effects, or the influence of aggressive environments. Crack wake closure and environment particularly alter near-threshold FCP behavior.

Considerable research has been directed at understanding the FCP properties of conventional high-strength aluminum alloys, particularly ingot metallurgy (I/M) 2XXX (Al-Cu) and 7XXX (Al-Zn-Cu-Mg) alloys. The rate of fatigue crack growth has been studied over a wide range of ΔK and R in AA2024 and AA7075 exposed to moist air, Figs. 6 and 7, respectively.[29–31,34] As R increases from -1.0 to 0.7 for AA2024 (Fig. 6) and from 0 to 0.9 for AA7075 (Fig. 7), near-threshold and Paris regime fatigue crack growth rates increase by 5–15-fold. This large mean stress effect is the result of decreased plasticity, roughness, and oxide induced crack closure.[22] High R limits crack wake surface contact during unloading, resulting in increased crack tip driving force and higher da/dN when plotted vs applied ΔK.

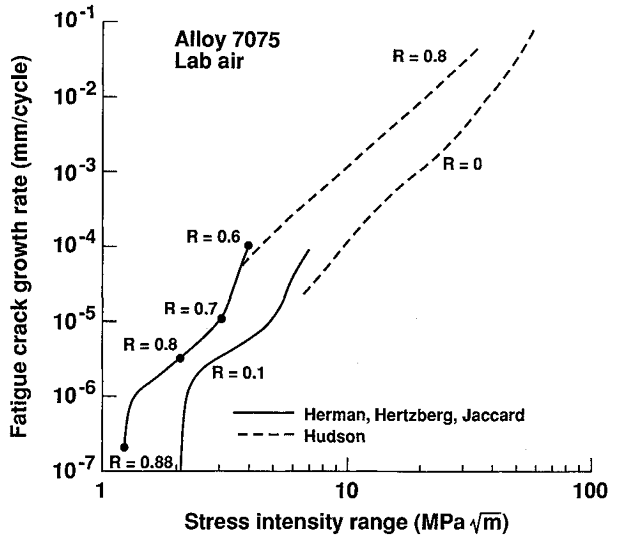

Fig. 7 FCP in AA7075 exposed to moist air over a wide range of cyclic stress intensities and for R ranging from 0 to 0.88.

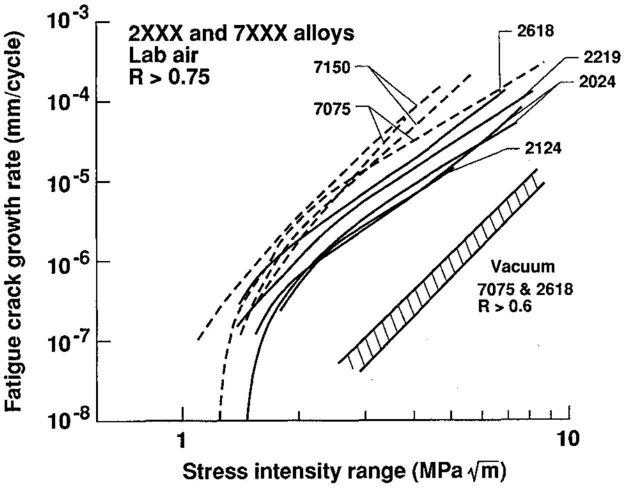

Fig. 8 Comparison of intrinsic (high R) fatigue crack growth rates for 2XXX and 7XXX series aluminum alloys in moist laboratory air and vacuum.

Extensive research has been performed on fatigue threshold stress intensity concepts. While specific data are abundant, little is known about crack tip damage mechanisms, and particularly environmental effects.[35,36] Figure 8 shows that laboratory air is damaging to 2000 and 7000 series alloys.[34,37–41] Near-threshold, intrinsic fatigue crack growth rates are a factor of 10–100 higher compared to vacuum results. The data shown in Fig. 8 reveal that 7000 series alloys exhibit increased growth rates compared to 2000 series alloys for FCP in moist air, suggesting an increased environmental sensitivity for the former.

Systematic studies of high-strength aluminum alloys established how microstructure affects fatigue crack propagation. Microstructural features which promote a heterogeneous distribution of concentrated plastic strain, and irreversible plastic strain, lead to undesirable local stress concentration and enhanced crack growth rate.[42] Additionally, microstructural effects on FCP are traceable to crack closure[43] and environmental mechanisms.[44] Strengthening precipitates are particularly important in these regards. Important variables include the volume fraction, size, coherency, and distribution of shearable precipitates; as well as precipitate-free zones near grain boundary particles.

Advanced Alloys

Advanced aluminum alloys have been developed in recent years, with the aim of increased stiffness, decreased density, and improved elevated temperature resistance. Promising materials include I/M Al-Li-based alloys, powder metallurgy (P/M) alloys, rapidly solidified P/M alloys, and metal matrix composites (MMC). Lithium increases the elastic modulus, and decreases the density of precipitation strengthened alloys. Alloys of commercial interest include Al-Li-Cu-Zr (AA2090 and AA2091), Al-Li-Cu-Mg-Zr (AA8090 and AA8091), and weldable Al-Li-Cu-Mg-Ag-Zr (Weldalite™, AA2095). High-strength and elevated temperature stability are achieved in powder metallurgy aluminum alloys by rapid solidification of novel compositions followed by thermal-mechanical consolidation which result in dispersions of fine intermetallic compounds and dramatically refined grain size. Examples include Al-Zn-Mg-Co (AA7091), high temperature Al-Fe-Si-V (AA8009), and lithium containing alloys such as Al-Li-Cu-Mg-Zr (644B). Discontinuous metal matrix composites attain enhanced strength and stiffness by the addition of reinforcing chopped fibers, whiskers, or particles to an aluminum alloy matrix. Silicon carbide whisker or particle-based composites with a 2XXX or 6XXX alloy matrix are particularly attractive, exhibiting essentially isotropic properties, and being shaped as well as joined by conventional methods.

Laboratory FCP data in Fig. 9 demonstrate that advanced aluminum alloys exhibit significantly different crack growth kinetics, particularly when studied at low R. Several of these alloys exhibit improved crack growth rate properties attributable to enhanced crack closure. For example, lithium based alloys exhibit substantially lower fatigue crack growth rates compared to conventional aluminum alloys and the new P/M alloys.[45] Similarly, Li-based I/M alloys exhibit higher ΔK_{th} (3–4 MPa$\sqrt{m}$) compared to P/M alloys (1–2.2 MPa$\sqrt{m}$) and discontinuous MMCs (2–3 MPa$\sqrt{m}$). The excellent FCP resistance of Al-Li alloys is due to roughness induced crack closure derived from an unusually tortuous fatigue crack path. At high R, the dashed line in Fig. 9, Al-Li-based I/M alloys have reduced closure, resulting in increased FCP rates and lower thresholds. These da/dN and ΔK_{th} are comparable to values for P/M and discontinuous MMC alloys. For these alloys, FCP is characterized by low closure, resulting from flat and featureless crack paths.[43] Crack growth rates are accordingly increased, and ΔK_{th} values are decreased at all R values.

Short Crack Problem

During the last decade, the growth behavior of small or short fatigue cracks, sized between 5 μm and 5 mm in metallic materials, has received worldwide attention.[46–52] (The "short" crack is generally defined as having a physically limited length, but intersecting many grains along the crack front. The "small" crack is defined as being contained within a single grain; both length and crack front perimeter are of restricted dimension.

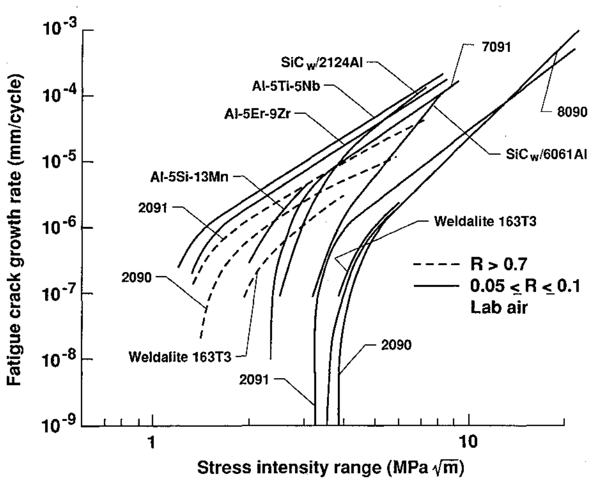

Fig. 9 Comparison of the fatigue crack growth rate characteristics of high strength I/M Al-Li alloys, P/M aluminum alloys and discontinuously reinforced aluminum alloy MMCs.

Short is used here for each type of crack.) When correlated based on linear elastic fracture mechanics and applied ΔK, short cracks can grow at unexpectedly rapid rates and well below the large crack threshold for $R > 0$ loading in aluminum, aluminum-lithium, and titanium alloys.[47] For steels, however, short crack and large crack behaviors are often, but not always, identical.[50,53] At stress concentrations typical of aircraft structures, short cracks initiate early in life if the local stress is above the fatigue limit. Because the initiation and short crack growth regimes are a substantial fraction of total life, erroneous data and nonconservative predictions on the growth rates of short cracks have a major impact on the fracture mechanics approach indicated in Fig. 1. As an example, 90% of the life of a notched specimen of AA2024-T3 was associated with the growth of cracks from 20 μm to 2 mm for $R = -1$ loading.[46] Similarly, 80% of the life of a welded steel pipe carrying H_2S contaminated oil was associated with fatigue crack growth from a 0.5-mm defect to a depth of 2.0 mm.[8]

The growth of short fatigue cracks is strongly influenced by load history, stress level, material microstructure, and environment. The growth differences between short and long cracks, at the same applied ΔK, are particularly pronounced for histories which include compressive loading, high applied stresses, and low R[47,53]; for alloys which exhibit extreme crack surface roughness which promotes crack closure[53]; and for FCP in aqueous environments.[50]

There are four accepted mechanisms for anomalous short crack behavior; each can affect fatigue in a given material/environment system.[54] They are based on 1) the loss of similitude which occurs when stress levels are high and small-scale yielding is exceeded; 2) local microstructural features which either promote noncontinuum plastic deformation, and thus rapid crack growth, or cause severe retardation; 3) the lack of crack closure in the early stage of crack growth when the shielding wake length is limited; and 4) the unique gas or aqueous electrolyte chemistry which may develop within a short occluded crack. The definition of a short crack depends on the mechanism(s) for the rapid growth rates.

Perhaps the most significant feature of short crack growth behavior is propagation at applied ΔK levels below the long crack threshold. This behavior impacts design life calculations. For example, long crack data that include ΔK_{th} cannot be used to treat the early stages of crack growth in aluminum alloys, because such data lead to prediction of infinite life for crack sizes as much as an order-of-magnitude larger than crack sizes that have been observed to grow to failure.[46,47] Thus, the use of long crack thresholds in damage tolerance and durability analyses is likely to be nonconservative.

Typical results on short crack growth behavior in AA2024-T3 are shown in Fig. 10. These fatigue data are from single-edge-notch tension specimens tested under $R = -2$ loading,[46] with three maximum applied stress levels S_{max}, noted by separate symbols. These short cracks tended to initiate at inclusion particle clusters on or near the notch root surface. The dashed line shows long crack data generated under the same conditions. The solid curves show predictions from an analytical closure model for each stress level.[55] These results show a strong influence of S_{max} on da/dN for short cracks, which grow faster at higher stress levels for the same applied ΔK. The predictions from the model show a similar stress level effect on the growth of short cracks. Although the initial crack growth rates from the model were in qualitative agreement with measured rates, the model predicted slower rates in the midrange than those measured. Irwin's plane strain condition was assumed for the growth of short cracks at the notch root. The actual behavior, however, may be closer to plane stress.

The prediction in Fig. 10 for an applied maximum stress level of 49 MPa demonstrates that a short crack can initiate and grow from a defect, but as the crack opening stresses rise, the crack can arrest. The data and model predictions in Fig. 10 strongly suggest that the lack of crack wake closure is a dominant mechanism for the anomalously rapid and subthreshold growth of short fatigue cracks in aluminum alloys. As such, it is possible to analytically describe the crack size effect for implementation in life prediction codes.

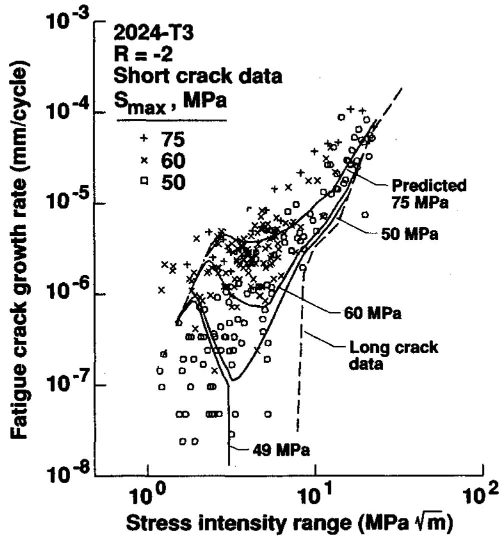

Fig. 10 Comparison of the FCP behavior of short and long cracks in AA2024-T3 in moist air.

Environmental Effects on Fatigue Crack Propagation

The surrounding environment, perhaps more than any other variable, exacerbates rates of FCP in aluminum alloys compared to cracking in vacuum or inert gases.[44] Crack tip damage accumulates with loading due to the synergistic interaction between cyclic plastic deformation and localized chemical reaction. While stress corrosion cracking (SCC) may occur during fatigue loading, cyclic deformation promotes environmental fatigue (or corrosion fatigue) below the threshold stress intensity for monotonic load cracking K_{ISCC}. As SCC-resistant aluminum alloys with high K_{ISCC} are developed, sub-K_{ISCC} environmental FCP assumes paramount importance.[56]

The application of fracture mechanics to environmental fatigue crack propagation has progressed over the past 25 yr.[5] Notable advances include 1) the demonstration of ΔK similitude,[57] 2) developments of experimental methods,[58] 3) phenomenological characterizations of crack growth rate behavior,[5,44] 4) identification of crack closure,[22] threshold,[59] and short crack issues,[48] 5) scientific studies of environmental fatigue damage mechanisms,[5] and 6) syntheses of life prediction methods.[6–9] This work shows that variables which are not important to mechanical fatigue in inert environments critically and interactively affect FCP in aggressive gases and liquids.

Embrittling Environments

Pure water vapor, moist air, and aqueous electrolytes with halogen ions (e.g., Cl^-) enhance rates of FCP in aluminum alloys near ambient temperature. An example is presented in Fig. 11 for an advanced Al-Cu-Li alloy (AA2090).[40,60] FCP was produced at a constant ΔK level that was incrementally reduced for a single K_{max} (17 MPa$\sqrt{m}$ in Fig. 11), resulting in increasing R (from 0.1 to 0.9 in Fig. 11). This method produced intrinsic FCP data minimally affected by crack closure. Similar, slow FCP rates are produced by cyclic loading in ultrahigh vacuum, purified helium, and molecular oxygen. Increased da/dN are recorded for high-purity water vapor, and aqueous NaCl solution with constant immersion and applied anodic polarization. Moist air is an aggressive environment relative to vacuum, with water vapor being the likely aggressive specie given the inert character of O_2.

Environmental effects on da/dN are accompanied by transitions in the microscopic fatigue crack path. For inert environments, fatigue proceeds by either {111}-type slip band cracking in alloys that exhibit localized planar slip, or by crack tip shear and blunting advance leading to striations. Environmental fatigue progresses along either high-angle grain boundaries for alloys that are susceptible to SCC, subgrain boundaries for unrecrystallized alloys, or crystallographic "cleavage" planes of the near-{100} type. The proportion of each mode depends on ΔK, environment activity, loading frequency, alloy microstructure, and specimen orientation. As an example in Fig. 11, environmental FCP in AA2090 occurred along subgrain boundaries at high ΔK, but by {100} cleavage at low ΔK when the cyclic plastic zone was contained within a single subgrain.[42,60] Stress intensity had no effect on the {111} slip band fatigue crack path for vacuum, helium, or oxygen.

Environmental FCP in aluminum alloys is broadly characterized by the compilation of $da/dN - \Delta K$ data in Fig. 12.[44] Laboratory studies of these effects are widely reported.[57,61–68] For immersion in 3% NaCl at moderate ΔK and low R, environmental FCP may occur either above or below K_{ISCC}; da/dN is increased by 4–100-fold relative to helium. Crack growth in alternate immersion and salt spray environments has not been examined. Distilled water causes corrosion fatigue in aluminum alloys, Cl^- is not a requisite for cracking. Only limited data exist for near-threshold ($da/dN < 10^{-6}$ mm/cycle) environmental FCP in aluminum alloys.[59,62,69]

Wei and his students,[5,63] Dicus,[66] and Bradshaw and Wheeler[67] conducted extensive studies of the deleterious effect of pure water vapor on fatigue in precipitation hardened aluminum alloys at moderate ΔK levels. da/dN values range between an upper bound, somewhat above rates for moist air, and a lower bound equal to rates for FCP in inert gas or vacuum. Typical data are presented in Fig. 13.

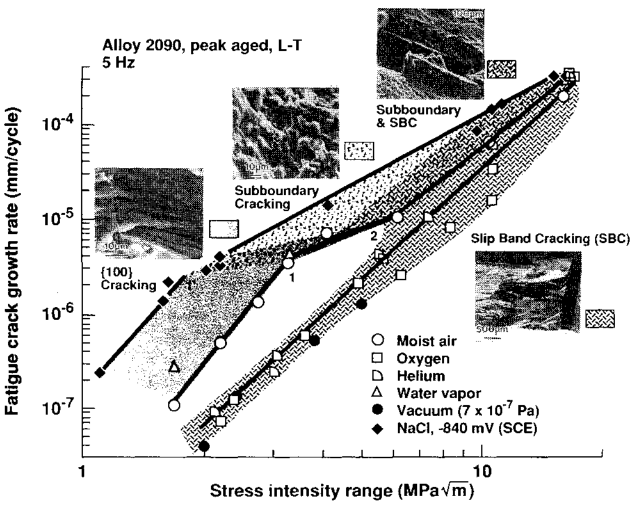

Fig. 11 Environmental effects on fatigue crack growth kinetics and microscopic cracking modes for Al-Li-Cu alloy 2090.

Environment-Crack Closure Interactions

Crack closure should be considered when mechanistically interpreting and applying environmental FCP data in life prediction, particularly for low R and near-threshold ΔK levels or unusually rough crack surfaces. Several closure mechanisms are unique to environmental FCP, including wedging

Table 1 Mechanical, environment chemical, and metallurgical variables affecting environmental fatigue crack propagation in aluminum alloys

Stress intensity range	Mean stress intensity
Crack size and shape	Specimen thickness
Loading frequency	Specimen orientation
Loading spectrum	Loading waveform
Solution Cl^-, H^+, O_2, S^{-2}	Water vapor pressure
Electrode potential	Water vapor O_2 level
Alloy microstructure	Alloy composition
Grain/subgrain size	Yield strength
Slip morphology	Work hardening
Precipitates	
Texture	

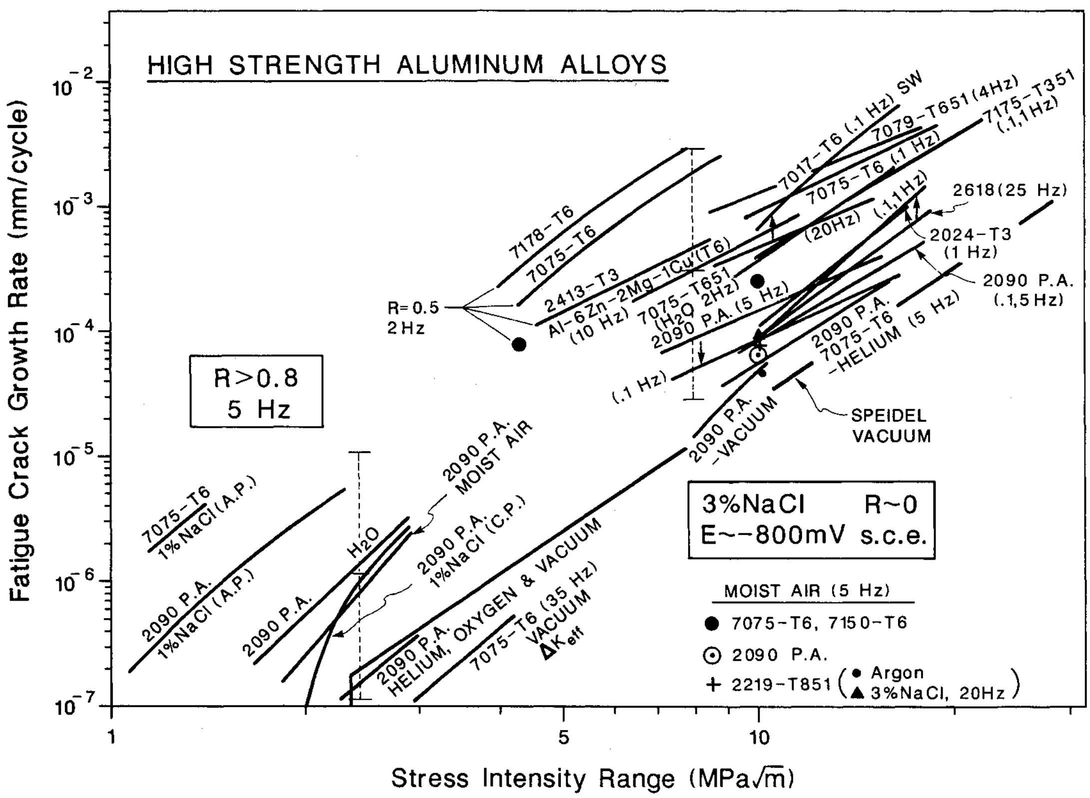

Fig. 12 Environmental fatigue crack growth rate data for high strength 2XXX and 7XXX series aluminum alloys.

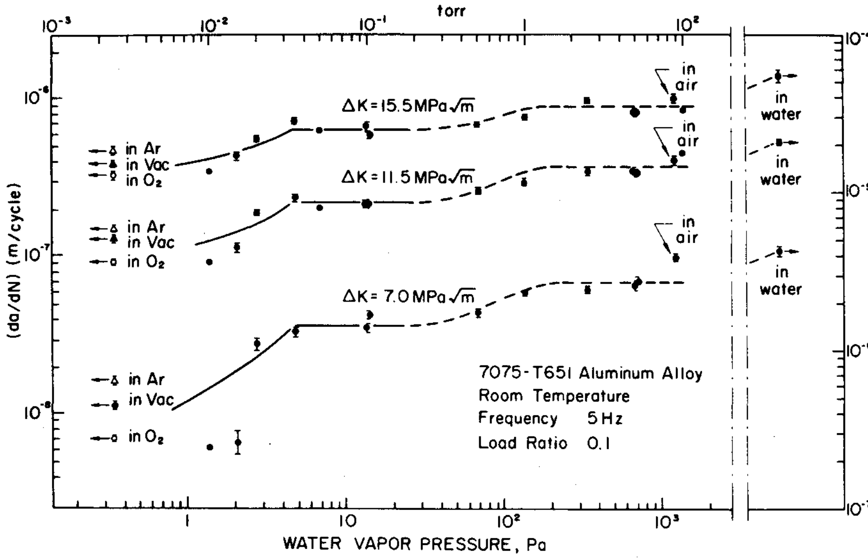

Fig. 13 Effect of water vapor pressure on crack growth rates in AA7075 at constant frequency and several ΔK levels (after Gao et al.[63]).

by corrosion debris or dislodged grains, enhanced surface roughness due to intergranular cracking, fluid pressure, and environment enhanced crack wake plasticity.[70] Conversely, environment may reduce closure, e.g., by causing planar transgranular cleavage cracking, as reported for AA2090 in NaCl.[60] Owing to the difficulty of measuring crack closure loads for specimens in gaseous or aqueous environments, studies on aluminum alloys have been limited to air formed oxide induced closure; an effect that is of secondary importance.[71]

Important Variables

The variables listed in Table 1 generally affect rates of environmental FCP in aluminum alloys, with complex interactions being the rule.[44] For example, environment greatly complicates the ΔK dependence of da/dN. The power law typical of inert environments, with a ΔK exponent from 2 to 4 and possible threshold behavior, is replaced by complex $da/dN - \Delta K$ relations typified by multiple power laws with exponents between 1–50. Typical examples of the difference in inert and environmental $da/dN - \Delta K$ relationships are indicated in Figs. 11 and 14.[60,62,64] Apart from decreasing crack closure with increasing stress ratio, the effect of R on intrinsic environmental FCP is poorly understood. Complex load history and load spectra effects have not been characterized.

Aluminum alloy composition and microstructure affect rates of environmental fatigue. Data in Fig. 12 demonstrate that 7000 alloys containing Zn, Mg, and Cu are more susceptible to cracking than 2000 series alloys (Al-Cu-Mg) including the new Al-Li-Cu compositions. This sensitivity parallels the well known susceptibility of 7000 alloys to intergranular SCC and hydrogen embrittlement.[56] Lin and Starke[72] argue that those compositions and precipitate morphologies which promote localized intense planar slip deformation are particularly sensitive to environmental fatigue. Wei and coworkers implicate magnesium, segregated to grain boundaries, as promoting environmental fatigue.[63,73] Microstructures and crack orientations which are sensitive to SCC, e.g., rolled plate with high-angle grain surfaces parallel to the crack plane, are similarly sensitive to environmental FCP.[56]

Environment activity (e.g., water vapor pressure or electrode potential for aqueous solutions) affects crack growth rates. For aqueous NaCl, da/dN increases with increasing anodic polarization, or with strong cathodic polarization, and decreases with mild cathodic polarization.[62,74] Growth rate increases with increasing water vapor pressure to a plateau level, as indicated in Fig. 14.[63] Sub-part-per-million levels of water vapor cause environmental fatigue, particularly at low frequency and high stress ratio.[62]

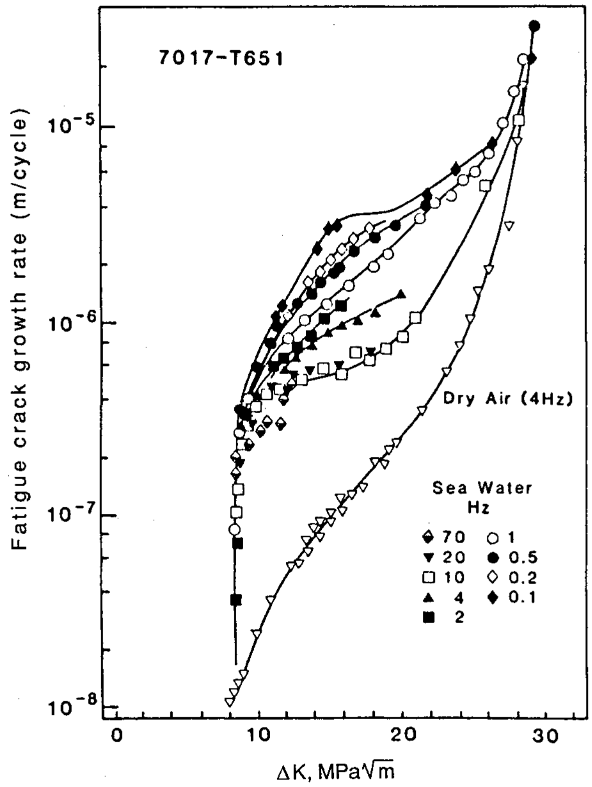

Fig. 14 Effects of environment and loading frequency on fatigue crack growth rates in AA7017 (after Holroyd and Hardie[64]).

Loading frequency is perhaps the most important variable which affects environmental fatigue. Crack growth rates generally increase with decreasing frequency because increased time per loading cycle enables increased mass transport and surface reactions which favor chemically based damage.[5] Environmental effects are often eliminated at sufficiently high loading rates; perhaps above 50 Hz, but depending on environmental transport and reaction kinetics. Frequency effects are predicted for environmental fatigue above K_{ISCC}, a purely time-dependent phenomena. Here, the environmental contribution to inert environment da/dN linearly increases with the time per load cycle while the cyclic stress intensity is above K_{ISCC}.[61,75,76] Crack growth below K_{ISCC} is both cycle and time-dependent, and is a more complex case to predict. A typical example of time-cycle-dependent environmental fatigue below K_{ISCC} is given in Fig. 14 for AA7017 in aqueous chloride.[64] While cracking in inert dry air is independent of frequency, environmental fatigue is enhanced by decreasing frequency from 70 to 0.1 Hz. Similar data were reported for water vapor; the results in Fig. 13 are well represented by the ratio of water vapor pressure to loading frequency.[63,66,67] In rare instances da/dN increases mildly with increasing frequency.[62]

Environmental Fatigue Damage Mechanisms

One of three mechanisms is typically cited to explain deleterious environmental effects on fatigue in aluminum alloys; hydrogen environment embrittlement, film rupture/electrochemical dissolution/repassivation, and crack surface film effects on dislocations.[5,44,77,78] These mechanisms are speculative and the topic of intense research.

Based on circumstantial evidence, hydrogen embrittlement is cited as a damage mechanism for environmental FCP of aluminum alloys in water vapor[5,59,62,63,69,79,80] and chloride electrolytes.[61,62,64,77] In this view atomic hydrogen chemically adsorbs on clean crack tip surfaces as the result of either 1) gas molecule-surface chemical reactions, or 2) electrochemical cathodic reduction of hydrogen ions or water molecules coupled with local anodic dissolution. Hydrogen production follows mass transport within the crack environment and precedes hydrogen atom diffusion in the crack tip plastic zone to sites of fatigue damage. Environmental crack growth rates are limited by one or more slow steps in this transport/reaction sequence.[5,63] The atomistic processes for hydrogen embrittlement are unknown.

Models of environmental fatigue were developed based on a repeating sequence of film rupture and anodic repassivation.[81,82] In this view localized plastic straining ruptures an otherwise protective passive film at the crack tip. Crack advance occurs during transient anodic dissolution of the metal at the film breach and while the surface repassivates. Quantitative models for da/dN include metal dissolution and repassivation kinetics, film ductility, and crack tip strain rate. This model has been extensively applied to steels in aqueous environments,[81] however, applications to aluminum alloys are limited.[83]

Given important assumptions and adjustable parameters, hydrogen and film rupture models semiquantitatively predict da/dN vs ΔK, as necessary to extrapolate environmental FCP data over a range of variables.[5,6,82] These expressions emphasize the mass transport and chemical reaction components of fatigue damage and are capable of predicting the effects of environment chemistry, metallurgical, and time variables. A typical result is the predicted exposure (water vapor pressure to loading frequency ratio) dependence of da/dN indicated by the solid lines in Fig. 13.[63] These models are, however, limited because of the complexity of the environmental fatigue process and because it is not possible to directly probe crack tip process zone damage on the microscopic scale.

Life Prediction and Environmental FCP

Existing life prediction codes do not adequately deal with complex, time-dependent environmental effects on fatigue crack propagation. Recent successes have been reported for steels in offshore oil and gas structures, and in piping and pressure vessel components of nuclear power systems.[6–9]

Several aspects of environmental FCP complicate fracture mechanics life prediction. The strong effect of loading frequency hinders the application of laboratory data, obtained over short time periods on the order of days, to describe the long life (viz., years) performance of a component in an aggressive environment. Laboratory work has emphasized constant amplitude loading; complex load spectra have not been employed in environmental FCP experiments. Component life prediction is further complicated by the many variables which affect crack growth rate behavior (e.g., Table 1). Lacking mechanistically based models, $da/dN - \Delta K$ data must be obtained for the time, mechanical, chemical, and metallurgical conditions of interest.

Variable Amplitude Loading

An improved understanding of the fatigue crack growth process under constant amplitude loading is essential in the development of fracture mechanics life prediction methods for variable amplitude loading. For spectrum loading, crack growth rates tend to span orders of magnitude and, consequently, an accurate description of constant amplitude $da/dN - \Delta K$ data over many orders of magnitude in rates is necessary to predict accurate lives. Constant amplitude data provide information on microstructural and environmental effects, ΔK_{th}, short crack effects, transitions in the ΔK-rate curve, flat-to-slant crack growth, constraint effects, nonplanar crack profiles, crack closure, stress level, and stress ratio effects. Comparable information for variable amplitude loading is lacking. For example, crack closure mechanisms must be understood and analysis methods developed to calculate the variation in closure as a function of load history.

A review of the current understanding of crack growth processes and the status of prediction methodologies under variable amplitude loading is given by Wanhill and Schijve.[84] They report an important observation from crack growth rate tests conducted under flight simulation loading. Flight simulation tests conducted on thin specimens of ductile alloys show an initial decrease in crack growth rate per flight with increasing fatigue crack length, whereas thicker specimens show an immediate rise in rates, as shown in Fig. 15.[85] The solid curves show test results for 2- and 10-mm-thick center crack tension specimens of AA2024-T351. Both specimens had a 4-mm sharp notch to initiate cracks and were subjected to the Mini-TWIST[86] load spectrum with a mean stress of 70 MPa. The dashed curves show predicted crack growth rates from the analytical crack closure model[17] using the variable constraint option[21,55] to correlate the constant amplitude data. The predicted rates agree with measured da/dN values, especially for the thicker specimen. Some differences were observed between the experiment and analyses in the early stages of growth in the thick specimen. This discrepancy may be due to faster crack growth in the interior of the specimen than at the surface. The early stage of growth in the thin specimen was well predicted by the closure model. Blom[87] has shown similar results under the TWIST spectrum, using the variable constraint method that was developed in the FASTRAN code.

Future Direction

The fracture mechanics approach provides an effective means to characterize and predict fatigue crack propagation in aer-

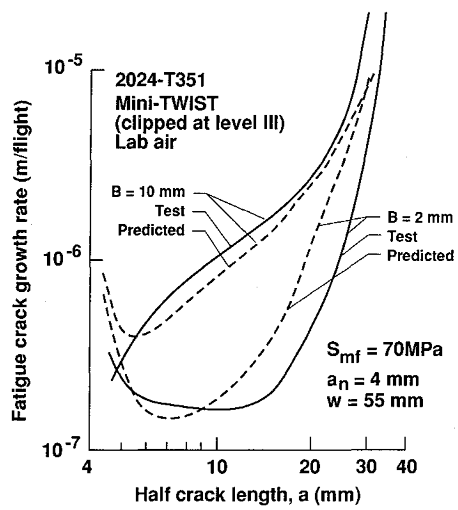

Fig. 15 Comparisons of experimental and predicted mean fatigue crack growth rates for AA2024-T351 under Mini-TWIST spectrum loading (test data from Wanhill[85]).

ospace aluminum alloy components. Even so, significant research and engineering uncertainties must be addressed.

Laboratory experiments should be conducted to determine 1) environmental effects on near-threshold FCP for varying frequency; 2) the FCP behavior of advanced light alloys and composites for varying environment and load history; 3) environmental FCP under spectrum loading, including the effects of over- and under-loads; 4) crack closure phenomena for FCP in aggressive environments; 5) quantitative fractographic descriptions of the micromechanisms of FCP; and 6) in situ monitoring of defect-based initiation, early crack growth, and closure evolution for small fatigue cracks in inert and aggressive environments.

Analytical modeling is required to describe 1) crack closure that results from surface roughness and corrosion debris, 2) crack tip process zone fatigue damage from interactive plasticity and environmental mechanisms, 3) the long term environmental fatigue life of a component by extrapolating short term laboratory data, 4) component fatigue life under complex spectrum loading and based on advanced crack closure models, and 5) mechanisms for short crack effects and associated influences on component life.

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