Fatigue Crack Growth Thresholds, Endurance Limits, and Design

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Foreword

This publication, *Fatigue Crack Growth Thresholds, Endurance Limits, and Design,* contains papers presented at the symposium of the same name held in Norfolk, Virginia, on 4–5 November 1998. The symposium was sponsored by ASTM Committee E8 on Fatigue and Fracture. The symposium co-chairmen were J. C. Newman, Jr. and R. S. Piascik, NASA Langley Research Center.

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Overview

Mechanisms

The technical session on fatigue-crack growth (FCG) threshold mechanisms was chaired by R. Pippan. Three mechanisms that influence thresholds, crack-tip closure, environment, and K_{max} effects, were discussed. A simplistic four-parameter model that describes FCG threshold behavior of elastic-plastic materials was presented. The proposed model was capable of predicting the R-ratio effects produced by "intrinsic" mechanisms and "extrinsic" shielding mechanisms. From this research, the basic FCG threshold behavior was characterized by two parameters, $K_{max/th}$ and $\Delta K_{th/int}$, which can be obtained from two tests conducted on a single specimen. A crack-tip closure concept based on the cyclic plasticity in the vicinity of a fatigue crack under threshold conditions was proposed.

The electron channeling contrast imaging (ECCI) technique was used to characterize crack-tip dislocation configuration and derive crack-tip plastic strain contours. From these results, the lower portion of the load-crack-tip-opening displacement curves was critically evaluated for crack-tip opening loads. This technique was used to study the fatigue-crack-growth-threshold behavior of quasi-two-dimensional structures, such as thin foils and films of various materials. Microstructure and environment based mechanisms and modeling for near-threshold FCG were presented. Here, three crack-growth regimes were suggested: (1) stage I single crystal crack growth, (2) stage II cracking along the normal to the applied load, and (3) a crystallographic stage which prevails near the threshold when the deformation at the crack-tip was localized within a single slip system. The damaging effects of water vapor environment were discussed in terms of hydrogen assisted crack propagation. Near threshold, K_{max} effects were investigated in ingot and powder metallurgy aluminium alloys. Results suggest that no single value of FCG threshold exist. Observations suggest that K_{max}-accelerated, closure free, near-threshold FCG was caused by changes in crack-tip process zone damage mechanism(s).

Test Procedures

Two sessions on loading and specimen-type effects were chaired by E. Phillips and R. Piascik. Research showed that the resistance-curve (R-curve) method to determine the threshold for fatigue-crack growth should allow more reliable application of ΔK_{th} values to engineering problems. A very simple technique to measure such R-curves was described and the results were shown to give effective thresholds. Application of the R-curve method leads to the Kitagawa diagram that can be used to estimate the fatigue limit as a function of defect size.

Different interpretations of the influence of K_{max} on ΔK_{th} were highlighted during the session. Research showed that a constant ΔK_{th} could be established and considered a material property based on the fatigue-crack-growth rates asymptotically approaching zero. While similar behavior was observed by others, a finite decrease in ΔK_{th} was noted for increased K_{max}; here, an increased K_{max} driving force was suggested and no constant FCG threshold was observed. A unique test procedure based upon the increase in threshold level was adopted to determine the maximum level of crack closure resulting from an overload. The

novel observations showed that FCP behavior at distances well beyond the overload plastic zone could be sensitive to prior overloads.

High (gigacycle) cycle fatigue studies showed that fatigue thresholds were about the same in conventional fatigue and in resonant fatigue if the computation of the stress-intensity factor (K) was correct. But there was a very large difference between the endurance limits at 10^6 cycles and 10^9 cycles. Results suggest that a life prediction approach based on ΔK_{th} was not safe because it does not account for an incubation nucleation process. Standard (ASTM E647) fatigue-crack-growth tests on nickel-based superalloy 718 along with crack-closure measurements were instrumental in reconciling data from different laboratories. But, the results did show that standard techniques could not explain increased closure from larger specimens. Similar differences in Ti-6222 threshold fatigue-crack-growth rates were observed using three standard test specimen configurations. Here, differences in threshold FCP rates could not be explained by crack-tip closure, suggesting possible crack length and load reduction procedure dependence on FCP behavior.

FCP under biaxial constant straining and periodic compressive straining was discussed. Accelerated FCP after compressive loading was related to flattening of fracture surface aspirates and reduced crack closure. For various biaxiality ratios, the ratios of the effective strain intensity factor range to constant amlitude strain intensity factor range at the threshold were found to be close to the ratios of the closure free fatigue limit obtained from effective strain-life to the constant amplitude fatigue limit.

Analysis

The session on analyses of fatigue-crack-growth-threshold behavior was chaired by T. Nicholas. Three papers in this session analyzed the behavior of fatigue cracks in the threshold regime using several different analysis methods. These methods were the elastic-plastic finite-element method (FEM), the Dugdale-type model, the BCS (Bilby, Cottrell and Swinden) model, and a discrete-dislocation model. Most of these methods only consider plasticity-induced closure in a continuum mechanics framework but the discrete-dislocation model was applied to a two-phase material with alternating regions of different yield stresses to simulate different grain structures.

Test measurements made during load-reduction procedures have indicated that the crack-opening stresses rise as the threshold was approached. In the literature, this rise has been attributed to roughness-, fretting-oxide-debris-, or plasticity-induced closure. These analysis methods were being investigated to see if threshold behavior could be predicted from only the plasticity-induced closure mechanism. Two-dimensional, elastic-plastic, finite-element crack-growth simulations of the load-reduction threshold test show a rise in the crack-opening stress (S_{open}/S_{max}) ratio as the ΔK levels were reduced, only if the initial ΔK level at the start of the load-reduction procedure was high enough. At low initial ΔK levels, the rise in the crack-opening-stress ratio was not predicted. Comparisons made between the FEM and the strip-yield model, FASTRAN, showed good agreement under plane-stress conditions. The rise in the closure level was caused by remote closure at the site of the initiation point for the load-reduction procedure. Because both of these analyses were two-dimensional, in nature, a remaining question was whether three-dimensional effects could cause a rise in closure even at the low ΔK levels due to the plane-stress regions near the free surfaces. The strip-yield model demonstrated that the plastic deformations even with the low ΔK levels were still a dominant factor for crack-face interference near threshold conditions.

The study of a homogeneous material with the dislocation model showed the existence of an intrinsic threshold in the near threshold regime due to the dislocation nature of plasticity. Incorporating micro-structural features (alternating grain structure) into the analysis, it was

shown that the intrinsic threshold value was determined only by the mechanism for dislocation generation and does not depend on micro-structural details like the grain size. However, in the near threshold regime and in the lower Paris regime the plastic deformation and the crack-growth rates are severely influenced by microstructure. Only in the upper Paris regime, where cyclic plastic-zone size exceeds several times the micro-structural length scale, usual continuum plasticity mechanics was appropriate to describe the events at the crack tip.

Applications

R. Rice and G. Marci chaired two sessions on applications of threshold concepts and endurance limits to aerospace and structural materials. The impact of a number of testing variables on the measurement of fatigue-crack-growth thresholds, in particular ASTM E647, was discussed. Applicability of the original E647 recommendations in light of some recent advances was also discussed. In addition, the effects of some commonly overlooked parameters, such as residual stress and environment, on the measurement and interpretation of crack-growth thresholds were presented.

A model using small-crack data to estimate the stress-life (S-N) response of cast aluminum alloys tested at high stress levels (50 to 90% of the yield stress) under $R = -1$ conditions was developed. The tradition LEFM model, with small-crack data, was inadequate in predicting the S-N behavior at the high stress levels. Perhaps, the use of non-linear fracture mechanics concepts, such as the cyclic J integral, would have improved the life predictions at the high stress levels. In another paper, the cyclic resistance-curve method was used to correlate fatigue limits for structural carbon steel components with small defects (ranging in length from 0.16 to 4 mm's). The threshold condition of crack growth from these small cracks was given by a constant value of the effective-stress-intensity-factor range irrespective of crack length and stress ratio ($R = 0$ to -2). Haigh (stress amplitude mean stress) diagrams for the endurance limit were successfully derived from the arrest condition of nucleated small cracks in smooth specimens.

Fatigue-crack-growth rate tests on cast nickel-aluminum bronze (NAB) and NAB weld metal specimens were conducted to determine the threshold for fatigue-crack growth (ΔK_{th}), per ASTM E647. Compared to the values for cast NAB, higher ΔK_{th} values and higher crack-closure levels in NAB weld metal tests were noted, due to the residual stresses in the weldment. The cracking behavior of a Ti-6246 alloy under cyclic loading at different levels of mean stress was studied, with special attention to the near-threshold fatigue-crack growth regime, and to possible coupled effects of corrosion and creep. The near-threshold crack growth at low K_{max} (i.e. low R ratio) was shown to be highly sensitive to the environment, and a predominant detrimental influence of water vapor was observed, even under very low partial pressure. This behavior was suspected to be related to a contribution of stress corrosion cracking induced by water vapor when some conditions favoring a localization of the deformation and the attainment of a critical embrittlement are fulfilled.

A method was derived from fracture mechanics to assess the effects of stress concentrations in components. The approach was based on an extension of the well-known critical-distance concept. This concept was tested using data from specimens containing short cracks and circular notches of various sizes and was successfully applied to the analysis of a component in service. In another paper on structural components, fatigue test data were presented for a transverse stiffener specimen made of a typical bridge steel. The specimens were tested under variable-amplitude fatigue loading for up to 250,000,000 cycles. A fracture-mechanics model was used to predict the variable-amplitude fatigue lives of the transverse stiffener specimens.

Fatigue-crack-growth thresholds were determined for 304 stainless steel, nickel-base weld metal alloy 182, nickel-base alloy 600, and low-alloy steel in air at ambient temperature and in high-temperature water and steam. A relatively inexpensive and time-saving method for measuring fatigue-crack-growth thresholds, and fatigue crack growth rates at low ΔK-values, was used in the tests. The method was a ΔK-decreasing test with constant K_{max}.

Defects in several thick-wall castings made of cast iron were statistically evaluated. A fracture-mechanics based model involving hardness and square-root of the defect area successfully related the defect size to the experimentally observed fatigue limit. The model also correlated the torsion and tension endurance limits. Endurance limits as a function of mean stress were presented in the form of Haigh diagrams.

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