Recent Advances in Fatigue Life Analysis Methods for Aerospace Applications

ARVIND NAGAR
Fatigue, Fracture and Reliability Group, Structural Integrity Branch, Structures Division, AFWAL Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio 45433, USA

ABSTRACT

The fracture mechanics concepts to predict crack growth behavior under service simulated loads from experimental data are reviewed. The mechanics and mechanisms derived from microscopic and macroscopic crack surface observations and developed from analysis of experimental data under normal and elevated temperatures are discussed. The fracture mechanics parameters for cyclic, time dependent and mixed cyclic-rate dependent damage for airframe crack configurations are presented. A discussion of fatigue life analysis including crack growth behavior due to retardation and acceleration of a steady growing crack is provided. The proposed extensions of existing methods for applications at elevated temperatures are discussed.

KEYWORDS

Aerospace structures; life analysis methods; crack growth; crack length measurement; load-interactions; elevated temperature fracture mechanics

INTRODUCTION

Safe and economic operations of modern engineering structures require development of fracture mechanics for structural design, construction and inspection.. The fracture mechanics concepts have been applied to design airframe structures and in recent years have been extended to all primary systems including the engine components, avionics equipment, hydraulic and mechanical systems and landing gears as well as composites. Earlier life life analysis methods for engine systems yielded conservative life estimates. These systems are now being designed based on damage tolerance concepts following airframe design practices. A brief review of recent developments in elevated temperature fracture mechanics was presented earlier (Nagar, 1988). An application of fracture mechanics to develop failure free operating periods of life for aircraft avionics equipment is discussed by Burkhard et.al. at this conference.

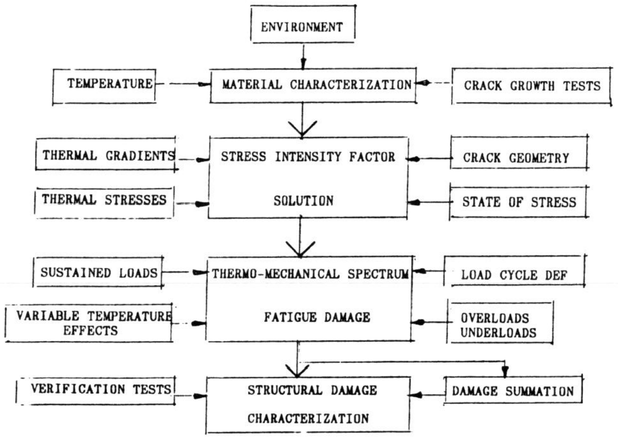

Fig. 1. Components of life analysis methodology for fatigue crack growth

This paper discusses recent advances in various areas of fracture mechanics for applications to aerospace life analysis methodology including the latest in analytic methods for stress intensity factor solutions, incorporation of elevated temperature effects on crack growth and life analysis. A brief review of new experimental techniques for crack measurements at elevated temperatures is provided.

LIFE ANALYSIS OF AEROSPACE STRUCTURES

Past functional impairments and failures of aerospace vehicles have been caused by cracks due to fatigue during maneuvering or stress corrosion under environment. Characteristically, the corrosion cracking occurs in a certain class of materials such as high strength forgings and is not due to primary loading. A proper material selection and anti-corrosive design techniques can effectively minimize and prevent corrosion cracking. The fatigue cracking occurs due to repeated reversals of inelastic deformation and is difficult to prevent. Thus, fatigue is one of the most important governing factors of structural integrity (Gallagher et. al., 1984).

Prediction of Crack Initiation

The total life of a structural member is the sum of the crack initiation period and the crack propagation life.The aerospace industry uses several methods for prediction of crack initiation. The Miner's rule for accumulative damage is based on experimental stress-life curves. Load interaction or sequence effects are not incorporated. Other methods are based on strain amplitudes. An energy based parameter representing the amount of energy dissipated as the material undergoes hysteresis has successfully correlated fatigue lives. Since certain structures are crack initiation controlled and the period of crack initiation consumes most of the economic life, U.S Air Force has developed specifications for durability together with those for damage tolerance (MIL-A-87221, 1985).

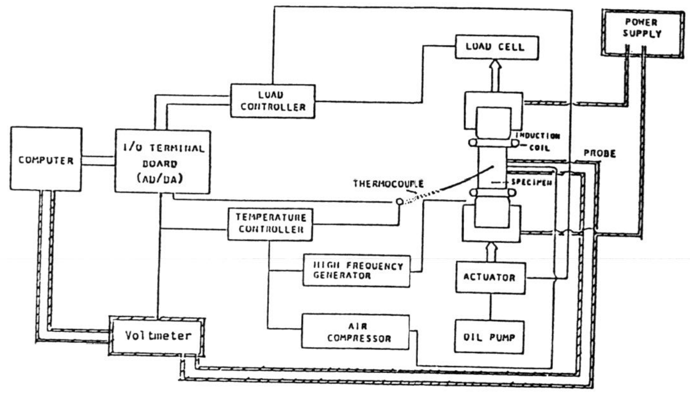

Fig. 2. An automated crack growth measurement system for thermo-mechanical fatigue loads

The durability assumes existence of small flaws in the structure and an analysis for durability requires determination of initial crack size distributions and the distribution of time for crack initiation (a detectable crack size). A discussion of the effects of material quality on airframe structural durability using probabilistic fracture mechanics analysis is presented by Magnusen et. al. at this conference. The short crack effects on crack growth behavior with initial cracks from 50 microns to 2 mm have been studied in nickel base superalloys and aluminum alloys (Pelloux, 1986). The transition length of a crack for which LEFM based applies becomes important from practical point of view. If the crack in the short crack regime can be reliably detected and measured the crack growth can be incorporated in crack life calculations.

Crack Growth Analysis Methodology

The structural life during crack growth stage can be calculated more reliably since a dominant crack exists and fracture mechanics concepts are generally applicable with experimental measurements being made on an engineering scale. The life predictions using such methods require accurate measurement of crack growth rates and calculation of applicable damage parameters which relate operating loads with the growing crack length. Various components of crack growth analysis methodology are presented in Fig. 1. Fracture characterization of materials is an important task in life analysis. Crack growth rates under cyclic loads, threshold values with environment and frequency effects are measured. An accurate calculation of crack driving force to represent crack and structural geometry and loading such as stress intensity factor) is required. A simulation of flight loads in analysis have required consideration of variable load effects. For hot structures, crack growth due to temperatures, effects of thermal gradients, thermal stresses and thermo-mechanical load interaction effects are important areas.

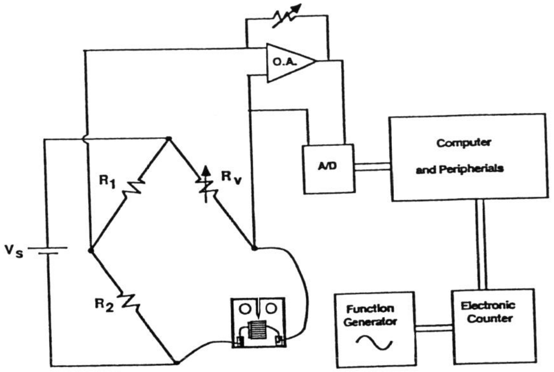

Fig. 3. A scheme for automation of crack measurement by micro-circuit grid technique

MATERIAL CHARACTERIZATION

Advanced designs of aerospace vehicles for performance at high velocities, high altitudes together with required reduced weight and improved fatigue resistance at elevated temperatures have required development of advanced alloys, composites and new experimental techniques.

Advanced Structural Alloys

In the past few years, the focus of fracture characterization have been on aluminum-lithium, powdered aluminum and superplastic formed aluminum alloys. An aluminum-iron-cerium alloy has demonstrated properties comparable to those of Ti 6-4. Advanced titanium alloys have been developed. As an example, isothermal forging of Ti-6Al-6V-2Sn in hot isostatically pressed powder form has shown improved ductility and fracture toughness. Fatigue and fracture characterization of titanium-aluminide alloys, Ti-25Al-10Nb-3V-1Mo and Ti-24Al-11Nb for applications upto 1200 F is currently being established. Experimental crack growth data on center cracked sheets and panels with central holes on Ti-6-2-4-2-S and Inconel 718 superalloy at normal and elevated temperatures have been established (Harmon et. al., 1988).

Advances in Composites

The USAF design requirements with respect to initial damage assumption, residual strength and damage growth limits for composites are evolving. The preliminary set of requirements has been established. Initial damage types during manufacturing include scratches, delamination, impact damage and hole fastener installation. The in-service initial damage assumption is based on fracture penetration, hail and bird strikes. The durability requirements for low level energy impact have been formulated.

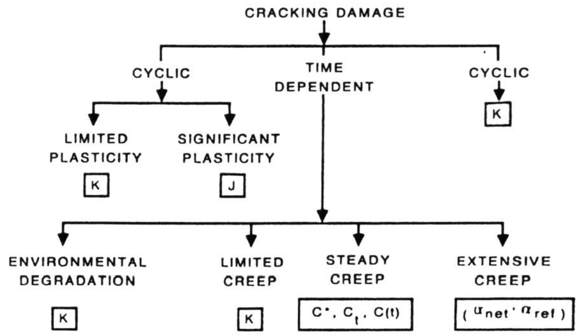

Fig. 4. Fracture mechanics based parameters for fracture and crack growth

Strength and fatigue life analysis techniques for metal matrix composite materials with continous fibers have been developed. The laminate strength predictions using Tsai-Hill criteria have shown good agreement with the experimental data. A computer program "MMCLIFE" for metal matrix composite life analysis have been developed (Harmon et.al., 1988). The program has the capability to predict crack initiation life, crack growth rate and residual strength. The routine is being modified for elevated temperature applications including spectrum loads with thermal profiles. The fiber matrix interface behavior under loads has shown to depend upon material, surface treatment and processing conditions. The K-calibration curves for some metal matrix composites have shown to be similar to those of isotropic materials. The rate of delamination may be determined very similar to rate of crack growth including the threshold and instability conditions.

Advances in Crack Measurement Techniques

Several advanced techniques for crack measurement have been explored and developed. An automated laser interferometric displacement measurement system using linear array cards have been developed. For elevated temperature applications, an automated crack measurement system (Fig. 2) with a calibration of crack growth under thermo-mechanical fatigue loads with d.c. electric potential drop have been demonstrateded. Several advanced concepts for direct measurement of crack automatically have been explored. The tip of of the propagating crack may be sensed by laser scattering, x-ray attenuation and digital imaging based systems. A microcircuit grid technique for automated crack measurement (Figure 3) is currently being developed. In the grid technique, the propagation of the crack tip is sensed by a grid bonded ahead of the crack. The advanced grid systems are capable of monitoring the resistance change and provide a more uniform change in resistance at the crack tip (Nagar et. al., 1988). This method has the distinct advantage that the calibration of the crack length is not required.

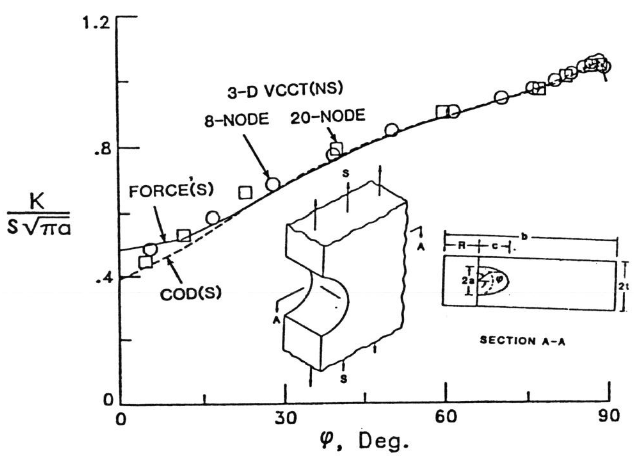

Fig. 5. A comparison of K solution using a virtual crack closure technique with force and COD methods

More recently a real time viewing of a growing crack at high magnifications have been developed at NASA (Telesman et.al., 1988). A fatigue loading stage inside a scanning electron microscope has been developed. A video tape recorder and a monitor allows repeated test viewing to study details of fatigue damage processes.

CRACK GROWTH PARAMETERS

Fracture mechanics based parameters for fracture and crack growth in structural alloys are listed in Fig. 4.The applicable crack correlating parameter depends upon the deformation processes, material ductility and the operating environment at the crack tip.

LEFM Based Parameters

For small scale plastic deformation of the crack tip region and conditions of linear elastic fracture mechanics, the cyclic crack growth is characterized by the stress intensity factor ''K''. A virtual crack closure technique for calculating stress intensity factors for cracked three dimensional bodies has recently been developed (Shivakumar et.al., 1988). This technique uses non-singular elements. The results have been applied to a surface crack emenating from a semicircular edge notch. (Fig. 5). An excellent agreement of results with force and crack opening displacement methods of finite element is obtained. Achenbach-Petroski method using influence functions have been used to determine the stress intensity factors and the strain energy release rates for residual stress and strain fields near the cracks in cold worked holes. A good agreement with bolt hole crack solutions have been obtained.

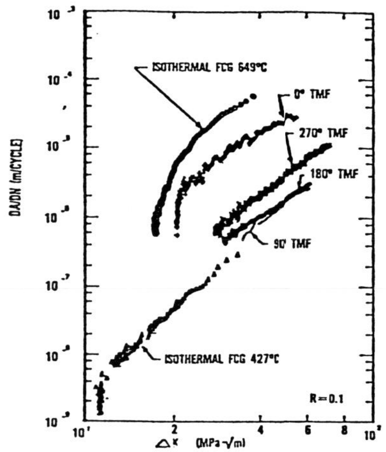

Fig. 6. Effects of thermo-mechanical fatigue cycling on crack growth in IN 718

Under thermal environment, several other factors may play a role depending upon the material and the level of temperature and time. The crack growth rate may become cycle dependent, time dependent or combined. If the crack tip material acts as creep brittle or exhibits sensitivity to environment, the crack growth rate may still be correlated by ''K'' (Nagar, 1988). Also, the LEFM based strain intensity factor has shown good correlation with crack growth at elevated temperatures under strain control tests under even significant nonlinear deformations (Merchand et.al. 1986). The stress and the strain intensity factor solutions for elevated temperatures under such conditions are the same as those for normal temperatures.

In environmentally sensitive materials such as nickel base superalloys, the crack growth during cyclic and sustained loads at elevated temperatures is due to environmental degradation of the crack tip by oxidation [15]. The damage due to crack growth is time dependent and occurs faster than the rate of stress relaxation at the crack tip. For such conditions, the stress intensity factor has shown better correlation with crack growth.

Parameters for Creep Deformation

The crack growth behavior under creep deformation of the crack tip has been characterizeded using a variety of parameters. During crack growth, the crack tip stress relaxation processes are more rapid than the crack growth rates. A most widely used parameter for creep crack growth is the energy rate line integral, C*. The parameter C* has successfully characterized crack growth under steady state conditions. More recently, a crack tip parameter Ct has shown better correlation with experimental creep crack growth data (Saxena, 1986). It correlates crack growth under transition creep as well as for the steady state region and reduces to C* as the steady state conditions approach. For materials which demonstrate excessive creep deformation, the net section stress and the reference

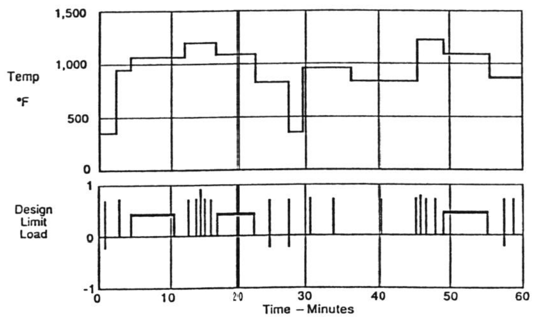

Fig. 7. Thermal-mechanical load profile for an advanced aerospace vehicle

stress have shown good correlation. Various path independent integrals using finite element techniques for extensive plastic-creep conditions with thermal gradients are currently under development.

CRACK GROWTH MODELS

Numerous models for fatigue crack growth have been proposed.For constant amplitude cycling, with all variables held constant, the crack growth rate can be related to the cyclic stress intensity factor using a material constant and an exponent such as the Paris law, at least in the subcritical region. Modified Walker and Forman's equations for mean stress effects on crack growth are commonly used in fracture analysis.

Elevated Temperature Crack Growth

The aircraft industry uses two empirical models for elevated temperature crack growth in engine components: a hyperbolic sine (SINH) model and a modified sigmoidal equation (MSE) model. Both models relate crack growth rate with the stress intensity factor range, stress ratio, frequency and hold time. The empirical constants for the models are determined from crack growth experiments on small coupons under various test conditions. Both models predict crack growth in superalloys at temperatures upto 650 C quite well. Both models overpredict crack growth at high ''K'' values and at long hold times (Haritos, 1985).

In recent years, several studies have been conducted to model effects of combined, cyclic and sustained loads at elevated temperatures on crack growth in superalloys and stainless steels. It has been observed that the crack growth effects of sustained loads at temperatures on crack growth in superalloys are very much like those of stress corrosion in high strength steels. For combined cyclic and sustained loads a superposition principle for damage has been extensively used, i.e.

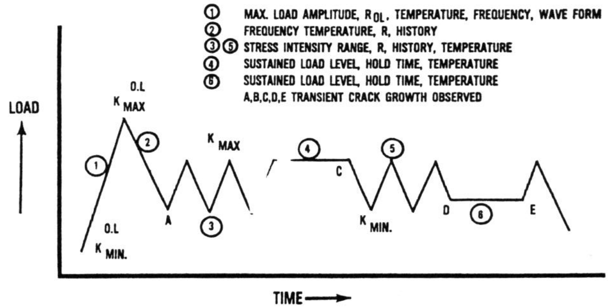

Fig. 8. Load interactions in thermo-mechanical spectrum load fatigue

$$da/dn\ (\text{Total}) = da/dn\ (\text{Cyclic}) + da/dn\ (\text{Time Dependent})$$

It is assumed that the cyclic and time dependent damages are linearly additive. The superposition principle has also been applied to crack growth under non-isothermal conditions. The correlation of experimental data in IN 718 for holding at 537 C, 593 C and 649 C during thermal cycling from 537 C to 649 C was good (within a scatter factor of 2) for hold times upto 15 minutes (Haritos, et.al.,1985). An experimental program on center cracked panels of advanced titanium alloys Ti-6-2-4-2 is currently underway to evaluate the application of superposition principle under varying hold times dispersed in spectrum loads for an advanced fighter (Harmon, et.al., 1988).

Thermo-Mechanical Fatigue

To study the effects of variable loads and temperatures, a simple and systematic approach is thermo-mechanical fatigue (TMF) testing. In a TMF test, both the temperatures and the load cycles are applied in triangular or sinusoidal wave forms. The effects of in-phase and out of phase cycling on crack growth can be evaluated. Such a study was conducted on center cracked tension specimens of IN 718 (Heil et.al., 1987). The phase angle influences the crack growth behavior. The thermo-mechanical fatigue data is bounded by isothermal crack growth curves. The crack growth rates were highest when the load and thermal cycles were applied in phase (Fig. 6). The crack growth was predictable by the superposition model assuming that the time dependent damage occurs during the rising part of the load and when the crack growth rate is an increasing function.

A crack growth model based on equivalent hysteric "K" was recently proposed. The hysteretic ''K'' is derived from local stress-strain state. The time dependent portion of the total damage was based on the integration taken over the entire cycle (Sunder, 1988).

Recent experiments also show that the linear farcture mechanics can be applied to correlate crack growth under mechanical strain controlled tests. In a strain controlled test, the out of phase loading causes the most damage with strain intensity factor as the correlating parameter.

THERMO-MECHANICAL SPECTRUM LOAD FATIGUE

A load temperature profile for an advanced aerospace vehicle is shown in Fig. 7. It is noted that the maximum loads and maximum temperatures may or may not occur simultaneously. The design loads for service conditions for the structure are derived from assumed service usage in terms of determininstic and the probabilistic components. The variable loads can cause retardation, acceleration or delayed retardation of steady state crack growth. Such loads may also influence crack behavior in the threshold region. The sequencing, multiplicity of loads and stress ratio for overloads and underloads have shown significant effect on life. The cyclic load interruptions interspersed in a spectrum load pattern can also alter crack growth behavior. Thus a proper life analysis methodology takes into account the load ordering, sequence of missions, spectrum editing (truncation and clipping of loads), and cycle counting.

Programmed block loads are often applied to predict crack growth during in flight conditions. The effect of ordering sequence of loads on life depend on the block size . A small block of 40 cycles shows little difference whether loads are applied in a low-high, a low-high-low or high-low sequence. However, if the block size is increased to 40,000 cycles, the crack growth life enhances by a factor of 3.

Load Interaction Models

Several load interaction mechanisms have been proposed for crack growth retardation and acceleration due to overloads and underloads including:

- Crack Closure
- Crack Tip Reversed Plastic Zone
- Crack Tip Sharpening and Blunting
- Crack Tip Prestrain
- Crack Tip Strainhardening
- Mean Stress
- Crack Tip Dislocation Structure

Fleck and Smith have argued that only the mean stress is able to explain all the load interaction effects and that under constant amplitude, the mean stress relaxes to zero due to cyclic creep, (Fleck and Smith, 1984). Other reports conclude that the crack growth retardation effects are caused by perturbations in residual stresses (Gallagher, 1984).

Several models have been proposed to account for retardation effects including:

- The Yield Zone Based Models
- Models Based on Crack Closure
- Strip Yield Models
- Strip Yield and Closure Models
- R.M.S "K" Approach
- Interpolation Models

A generalized Willenborg model in its modified form for overload shut off ratio and the threshold stress intensity factor is extensively used by the Air Force and the aerospace industry. The Willenborg model is based on length of yield zone formed by the overload. However, it has been argued that the concept of effective maximum stress intensity factor used in this model is non-realistic (Schijve, 1987). The latest developments in load interaction modeling are based on combination of closure and Dugdale plastic strip models. One of the advantages of the strip zone models is that the plain strain-plain stress effects can be included.

Load Interaction Effects at Elevated Temperatures

The load interaction effects under spectrum thermo-mechanical loads become very complicated. An on-going program is devoted to establish these effects in advanced titanium and superalloy 718 sheets (Harmon et.al., 1988). For elevated temperature applications, the following interaction effects on crack growth may be anticipated:

- Overloads
- Underloads
- Sustained Loads
- Cyclic Loads
- Variable temperatures

They may assume any combination of two or more in a given situation. Also, at each intersection of these thermo-mechanical spectrum fatigue loads the transient crack growth behavior is expected (Fig. 8). Various models at elevated temperatures has been explored. A modified SINH model to study the effects of single overloads in superalloys, Waspaloy and IN 100 was proposed. The effects of the magnitude of single overloads for IN 100 at 649 C has been studied. For an overload ratio of 1.5 and the overload applied every 40 cycles, a crack growth reduction by a factor of four is observed compared to constant load amplitude cycling at a stress ratio of .5. The retardation effect increases with the number of cycles. As the number of cycles between overloads is reduced to five, the retardation effect becomes almost negligible. The overloads in airframes are normally larger and are less frequent compared to those in engines. The effect of overload frequency was more significant in a Waspaloy (Larsen et. al.,1985).

Willenborg and interpolative SINH models correlate retardation effects under major excursions. However, the effects of compressive overloads and sustained load crack growth behavior is not correlated. It may be noted that if the specimens are too thin, the state of plane stress may develop and the plastic zones become comparable to the thickness and mixed mode crack propagation may result. At high temperatures, the mixed mode occurs at higher ''K'' than at room temperature. The crack growth retardation in a mixed cyclic-sustained load test with load held below maximum has been studied. Such a loading may be viewed as an overload applied to an otherwise sustained load. An overload model based on Wheeler's plastic zone size concept was developed. The length of plastic zone is calculated assuming plane stress conditions at the crack tip. An effective stress intensity factor which relates the value of stress intensity factor at sustained load with two constants derived from relative plastic zone length is proposed. The proposed model's predictions have been compared with experimental data from compact tension specimens in IN 718 at 649 C under constant ''K'' conditions. The load was held at 50, 80, and 100 percent of the maximum load value for time intervals from 0 to 200 seconds. The analytic predictions are shown to agree quite well in air. It is shown that at a 50 percent value of the sustained load, a complete retardation of the crack growth is possible (Weersooriya and Nicholas, 1985).

An application of equivalent hysteretic ''K'' approach to crack growth under spectrum load history is currently underway (Sunder, 1988). Also, another program for the effects of retardation in Willenborg model with plastic zone size adjustments for reduction in the yield strength at elevated temperatures is near completion (Harmon et. al., 1988).

SUMMARY AND CONCLUSIONS

Recent advances in life analysis methods are reported. New crack growth measurement techniques have been developed. A method of caustics to measure residual stresses near drilled holes have been developed. A real time viewing of the fatigue damage processes during crack growth has been accomplished. New analytic methods using weight or influence functions to determine the stress intensity factors and strain energy release rates for cold worked holes and holes with corner cracks have been developed. Modifications of CRKGRO to account for elevated temperature effects on crack growth due to change in plastic zone size and effect of hold time have been incorporated. Spectrum life analysis methods for advanced titanium alloys for temperature ranges upto 800 F have been developed. The life analysis techniques for metal matrix composites for applications up to 1200 F are being explored. Micromechanics and macromechanics approaches are being pursued to predict crack initiation and propagation.

REFERENCES

Military Specification, USAF MIL-A-87221 (1985), General Specifications for Aircraft Structures.

Bensussan,P.L. and Pelloux,R.M.(1985), Creep Crack Growth in 2219-T851 Aluminum Alloys: Applicability of Fracture Mechanics Concepts, Proceedings of the Sixth International Conference on Fracture.

Fleck, N.A. and Smith, P.A.(1984), A Discussion of Mechanisms of Accelerated and Retarded Fatigue Crack Growth, Advances in Fracture Research, ICF 6, New Delhi, India.

Gallagher, J. P. and Engle, R.M.(1984), USAF Damage Tolerance Design Handbook: Guidelines for the Analysis and Design of Damage Tolerant Aircraft Structures, AFWAL-TR-82-3073.

Haritos,G.K.,et.al.(1985), Sustained Load Crack Growth in IN 718 Under Nonisothermal Conditions, Journal of Engineering Materials and Technology, Transactions of the ASME.

Haritos,G.K. (1985), Evaluation of Crack Growth Models for Elevated Temperature Fatigue, Presented at the 18th National Symposium on Fracture Mechanics, American Society for Testing and Materials.

Harmon, D. M., Saff, C.R. and Burns, J. (1988), Development of an Elevated Temperature Crack Growth Routine, AIAA Paper No. 88-2387.

Harmon, D.M., Saff, C.R. and Graves, D.L. (1988), Strength and Life Prediction for Metal Matrix Composites, 9th ASTM Symposium on Composite Materials.

Heil,M.L.,et.al. (1987) , Crack Growth in Alloy 718 under Thermal-Mechanical Cycling, Thermal Stress, Material Deformation, and Thermo-Mechanical Fatigue, PVP-Vol. 123, ASME.

Larsen,J.M. and Nicholas,T. (1985), Cumulative Damage Modeling of Fatigue Crack Growth in Turbine Engine Materials, Engineering Fracture Mechanics, 22.

Merchand and Pelloux, R.M. (1986), A Computerized Test System for Thermo-Mechanical Fatigue Loading, Journal of Testing and Evaluation, 14.

Nagar, A. (1988), A Review of High Temperature Fracture Mechanics for Hypervelocity Vehicle Applications, AIAA Paper No. 88-2386.

Nagar, A., Stuffle, K., Cutler, R., Shetty, D. and Virker, A. (1988), A Microcircuit Grid Technique for Fatigue Crack Growth at Elevated Temperatures, Conference Proceedings, 6th Meeting, International Congress on Experimental Mechanics.

Nicholas,T. and Weerasooriya,T. (1986) , Hold Time Effects in Elevated Temperature Fatigue Crack Propagatiopn, Fracture Mechanics, 17th Volume, ASTM STP 905.

Pelloux, R.M. (1986), A Study of Fatigue Behavior of Short Cracks in Nickel Based Superalloys, AFOSR-TR-86-0224.

Sadanand,K. (1985),Theoretical Aspects of Fatigue and Creep Crack Growth, Proceedings of the Sixth International Conference on Fracture, New Delhi, India.

Saxena,A. (1986), Creep Crack Growth Under Non-Steady State Conditions, ASTM STP 905.

Schijve, J. (1987), Fatigue Crack Growth Predictions for Variable Amplitude and Spectrum Loading, Delft University Report LR-526.

Shivakumar, K. N. et. al. (1988), A Virtual Crack Closure Technique for Calculating Stress Intensity Factors for Cracked 3 Dimensional Bodies, Int. J. Fracture, 36.

Sunder,R., (1987), Analysis of Crack Growth Under Programmed Load-Temperature History in a Nickel Base Superalloy, International Symposium on Stress Corrosion Cracking, American Society for Testing and Materials.

Telesman, J. and Kantzos, R. (1988), Fatigue Crack Growth Behavior of Simple Crystal Alloy as Observed Thru an In-Situ Fatigue Loading Stage, 2nd Int. SAMPE Metals Conference.

Weerasooriya,T. and Nicholas,T. (1985), Overload Effects in Sustained Load Crack Growth in Inconel 718e, Air Force Wright Aeronautical Laboratories Report No. AFWAL-TR-85-4121.