FATIGUE LIFE PREDICTION MODELING FOR TURBINE HOT SECTION MATERIALS

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ABSTRACT

This paper presents a summary of the life prediction methods developed under the NASA Lewis Research Center's Hot Section Technology (HOST) program. A major objective of the fatigue and fracture efforts under the HOST program was to significantly improve the analytic life prediction tools used by the aeronautical gas turbine engine industry. This has been achieved in the areas of high-temperature thermal and mechanical fatigue of bare and coated high-temperature superalloys. Such technical improvements will eventually reduce life cycle costs.

The cyclic crack initiation and propagation resistance of nominally isotropic polycrystalline alloys and highly anisotropic single crystal alloys has been addressed. A sizeable data base has been generated for three alloys [cast PWA 1455 (B-1900+HF), wrought Inconel 718, and cast single crystal PWA 1480] in bare and coated conditions. Two coatings systems, diffusion aluminide (PWA 273) and plasma sprayed MCrAlY overlay (PWA 286) were employed.

Life prediction modeling efforts were devoted to creep-fatigue interaction, oxidation, coatings interactions, multiaxiality of stress-strain states, mean stress effects, cumulative damage, and thermomechanical fatigue. The fatigue crack initiation life models developed to date include the Cyclic Damage Accumulation (CDA) Model of Pratt & Whitney and the Total Strain Version of Strainrange Partitioning (TS-SRP) of NASA Lewis for nominally isotropic materials, and the Tensile Hysteretic Energy Model of Pratt & Whitney for anisotropic superalloys. The fatigue model being developed by the General Electric Company is based upon the concepts of Path-Independent Integrals (PII) for describing cyclic crack growth under complex non-linear response at the crack tip due to thermomechanical loading conditions. A micromechanistic oxidation crack extension model has been derived by researchers at Syracuse University. The models are described and discussed in the paper. Only limited verification has been achieved to-date as several of the technical programs are still in progress and the verification tasks are scheduled, quite naturally, near the conclusion of the program.

INTRODUCTION

To-date, efforts have concentrated on development of independent models for cyclic constitutive behavior, cyclic crack initiation, and cyclic crack propagation. The transition between crack initiation and crack propagation has not been thoroughly researched as yet, and the integration of these models into a unified life prediction method has not been addressed.

HOST Life Prediction Program

Table I lists the specific programs that have supported the fatigue and fracture life prediction efforts. Each will be discussed and the most significant of the numerous accomplishments will be pointed out. Space does not permit elaboration of the numerous methods nor of the experimental details. The reader is referred to the more thoroughly documented original references.
In addition to the Industrial Contracts and University Grants supported by the NASA HOST program, some funding was set aside to rejuvenate aging test facilities in the area of fatigue and fracture. The advanced, high-temperature fatigue and structures research laboratory at Lewis (McGaw and Bartolotta, 1987) is now operational, and in fact has grown to the point of requiring further expansion. The facility is equipped with the very latest closed-loop, strain-controlled machinery, and most importantly boasts a unique computerized nerve center for programmed test control; data taking, storage and retrieval; and data reduction and plotting.

**ISOTROPIC MATERIAL MODELING**

**Cyclic Crack Initiation**

The majority of usable cyclic lifetime of turbine engine hot section components is usually spent in what is called the "cyclic crack initiation" portion of the fatigue life. Strictly speaking, crack initiation does indeed contain a considerable amount of cyclic crack growth, although the physical size of the cracks is quite small. From an engineering point of view, any crack growth below a crack size of approximately 0.8 mm (1/32 in.) typically is included in the "initiation" portion of the life. Justification for this definition is based upon: (a) the inability to reliably detect cracks of smaller size, and (b) the inability of cyclic crack growth laws to adequately model cyclic extension of cracks smaller than this size. Such a definition of cyclic crack initiation is used in the development of the Pratt & Whitney Cyclic Damage Accumulation Model addressed in the next section.

**Pratt & Whitney Cyclic Damage Accumulation (CDA) model.** The interaction of creep with fatigue at high temperatures is being studied in detail under NASA/HOST Contract NAS3-23288, "Creep-Fatigue Life Prediction for Engine Hot Section Materials (Isotropics)" (Moreno, 1983, Moreno et al., 1986, and Nelson et al., 1986). This effort has investigated fundamental approaches to high temperature crack initiation life prediction using a cast nickel-base alloy, PWA 1455 (B990 + Hf) as the base material. During the program over 157 specimen tests were completed under loading conditions which consisted of monotonic tensile and creep tests as well as continuously cycled fatigue tests. A review of existing fatigue models was conducted, and desirable features of each of these were identified. A new method of high temperature fatigue life prediction called Cyclic Damage Accumulation (CDA) was subsequently developed which incorporates many of these features.

Complex loadings were introduced during the latter stages of the program to study the effects of thermomechanical fatigue, multiaxial loading, cumulative damage, environment, mean stress, and coatings. An additional 160 strain-controlled fatigue tests have been conducted as a part of these tasks. Three different surface treatments were utilized for the TMF and coated tests: bare (no coating), overlay NiCoCrAlY coated, and diffusion aluminide coated. Several refinements have been incorporated into the CDA life prediction model based on the results of these complex tests. The current form of the model for accumulated transgranular damage is given by Eq. (1).

\[
1 - \int_0^{N_f} \left( \frac{1}{\varepsilon_D} \right) \left( \frac{1}{G_{NL}} \right) \left( \frac{\Delta \sigma_{TR}}{\Delta \sigma_R} \right) \left( \frac{f_{OX}}{f_{OX_R}} \right) \left( \frac{D_{TD}}{D_{TD_R}} \right) dN
\]

where

- \(N_f\): Initiation life, transgranular mode
- \(\varepsilon_D\): Primary creep ductility
- \(G_{NL}\): Nonlinear damage accumulation function
- \(\Delta \sigma_{TR}\): Reference cyclic damage rate
- \(\sigma_{TR}\): Reference maximum tensile stress
- \(\Delta \sigma_R\): Stress range of current cycle
- \(f_{OX}\): Cyclic oxidation rate for current fatigue cycle
- \(f_{OX_R}\): Reference fatigue/cyclic oxidation rate

The basis for Eq. (1) is explained by Moreno (1983), Moreno et al. (1986), and Nelson (1986). A goal of the program to develop the CDA model was to limit the complexity of the experiments to determine the material behavior constants. For example, only monotonic creep tests and continuous cycling fatigue experiments are required to evaluate the constants in the first term of the CDA expression. The second term requires that cyclic oxidation measurements be made during fatigue testing.

Nonlinear damage accumulation calculations are now possible for both cycle-dependent and time-dependent cases. Modular terms which capture the effects of multiaxiality, coatings, and intergranular cracking are currently under development. The ability of the model to correlate thermomechanical fatigue and life prediction is being studied at Lewis (McGaw and Bartolotta, 1987) and in fact has grown to the point of requiring further expansion. The model is equipped with the very latest closed-loop, strain-controlled machinery, and most importantly boasts a unique computerized nerve center for programmed test control; data taking, storage and retrieval; and data reduction and plotting.
Here, materials and loading conditions result in strain levels that, while they are severe and produce low-cycle fatigue cracking, involve only small amounts of inelastic deformation within nominally elastic strain fields. The limited inelasticity produced locally may exert a significant influence on life. The type of inelastic strains present (time-dependent creep and time-independent plasticity) and the direction of the strains (tensile or compressive) can be quite important in governing the resultant cyclic crack initiation life. The total strain range versus life diagram. Entering the diagram with the known total strain range, the cyclic life is determined directly without having to calculate the magnitude of the inelastic strain range. Example life prediction calculations by the TS-SRP approach have been reported by Halford and Saltzman (1983), Moreno et al. (1985), and Saltzman and Halford (1988). The degree of success of the method is shown in Fig. 3. Here, the TS-SRP method was applied by Moreno et al. (1985) to a series of five different types of complex verification experiments performed on the nickel-base superalloy, B900 + Hf. A direct comparison of the TS-SRP approach with the CDA model also was made by Moreno et al. (1985), wherein the principal features of each method were emphasized. The TS-SRP model and the Pratt & Whitney CDA model were both designed for application to strain-driven fatigue loading conditions in the nominally elastic regime. Both methods are currently being adapted for application to TMF problems.

Cyclic Crack Propagation

Cyclic growth of cracks and defects in turbine engine hot section components is of considerable concern because of the lack of structural redundancy in the construction of these components. As such, crack growth to a critical fracture size must be prevented catastrophic fast fracture and subsequent loss of engine function. Typically, concern for fast fracture is associated more with rotating components than with static structures. For combustor liners, guide vanes, stationary spacers, and other nonrotating components, concern for cyclic crack growth is more economic in nature than safety-related. In the HOST fatigue and fracture program, two approaches to crack growth were taken. An engineering methodology was applied in an attempt to develop directly useful design tools, and a scientific approach examined the micromechanisms of crack extension at the crystallographic level and the interaction with oxidation phenomena.

General Electric Path-Independent Integral model

A major goal of the contract program with the General Electric Company is to develop reliable and accurate engineering life prediction capabilities to deal with cyclic crack growth at elevated temperatures. Several of the Path-Independent Integrals, \( J_x \), that have been proposed over the past few years have been shown to be
applicable to fracture mechanics calculations of cyclic crack growth under uniform and nonuniform thermal gradients and thermomechanical loadings. Specifically, the various Jx integrals proposed by Tada et al. (1973), Ainsworth et al. (1978), Blackburn et al. (1977), Kishimoto et al. (1980), and Atluri (1982) have been found suitable for analysis of crack stress fields involving nonlinear and time-dependent thermomechanical response (Kim and Orange, 1988). The traditional Rice J-Integral (Rice, 1968), however, becomes path dependent and loses its physical significance for thermomechanical loadings. Figure 5 compares the results of a series of calculations applied to an instrumented single edge notch specimen of Inconel 718 with a linear thermal gradient. The current program with the General Electric Company will continue into 1989, during which time one of the path-independent integrals will be selected for further verification under realistic thermomechanical loading conditions found in the hot section of gas turbine engines.

Syracuse University oxidation crack extension model. Liu and Oshida (1986) and Oshida and Liu (1988) have taken a micromechanistic approach to dealing with crack propagation in superalloys. A model of intermittent micro-rupture of grain boundary oxide has been proposed for high temperature fatigue crack extension. The model is outlined briefly below for the case of a trapezoidal waveform.

Oxygen arriving at a grain boundary crack tip must diffuse into the region ahead of the crack in order to form oxide along the grain boundary. When the crack tip grain boundary oxide, at a given stress level, reaches a critical size, 6a, the oxide will rupture and the crack will grow by the amount, 6a. The critical size, 6a, depends on the stress intensity level during the holding period. Once the crack tip has advanced to its new position, the process of grain boundary diffusion, grain boundary oxidation, and micro-rupture of the oxide is repeated. This process of micro-rupture of a crack tip grain boundary can recur intermittently during a fatigue cycle, and in fact, many micro-ruptures can take place. After each micro-rupture, the penetration of grain boundary oxide must start all over again from a “time” zero. The time interval, 6t, necessary to reach the critical size, 6a, is given by,

$$\delta t = \left( \frac{B}{D_{gb}} \right) \left( \frac{6a}{BB} \right)^{1/n}$$  \hspace{1cm} (9)

where

- B magnitude of the diffusion jumping vector or interatomic spacing
- D_{gb} grain boundary diffusion coefficient
- \beta, \beta' proportionality constants
- n positive exponent (less than unity)

The number of micro-ruptures during the holding period, \Delta t_H, is,

$$m = \Delta t_H \delta t = \left( \frac{\Delta t_H D_{gb}}{B} \right) \left( \frac{6a}{BB} \right)^{1/n}$$  \hspace{1cm} (10)

m is linearly proportional to the holding period and is inversely proportional to the frequency.

Fatigue crack growth per cycle is the sum of the micro-ruptures during the holding period,

$$\frac{da}{dN} = m \delta a$$  \hspace{1cm} (11)

From Eqs. (9) to (11) we obtain,

$$\frac{da}{dN} = \beta D_{gb} \left( \frac{6a}{BB} \right)^{1-n/n} \delta t \frac{\beta' D_{gb}}{f(B/6a)^{1-n/n}}$$

Note that \( \frac{da}{dN} \) is inversely proportional to frequency, f. Figure 5 taken from Liu and Oshida (1986) illustrates the success the approach has had in correlating crack growth under high temperature environments. The experimental results shown in the figure were obtained from the open literature.

ANISOTROPIC MATERIAL MODELING

Pratt & Whitney single crystal constitutive model. Because of the exceptionally strong link between the cyclic deformation mechanisms in single crystal alloys and the fatigue crack initiation process, it was deemed advisable to develop both the cyclic constitutive and cyclic crack initiation life prediction models within a single program. Furthermore, since single crystal alloys invariably require a protective coating for successful high-temperature applications, it was also necessary to develop a cyclic constitutive and life model for the coating systems. The constitutive models will be discussed in the following section.

A unified constitutive model has been formulated for PWA 1480 single crystal material and is currently in the final stages of development. The model uses the unified approach for computing all inelastic strain rather than the conventional approach of treating creep and plasticity separately. The model assumes that all inelastic behavior results from shear strains on each of the twelve octahedral and six cube slip systems and that the global inelastic strains are simply the sum of these slip systems strains. Slip system inelastic shear strain rates are governed by a set of viscoplastic equations which involve the slip system stresses and two evolutionary state variables. The general form of the equation governing inelastic shear strain on the rth slip system as given by Swanson (1987) is,

$$\dot{\gamma}_r = \frac{(\pi_r - \omega_r)}{K_r P - 1}$$  \hspace{1cm} (13)

where

- \( \dot{\gamma}_r \) inelastic shear strain rate on the slip system
- \( \pi_r \) effective stress acting on the slip system
- \( \omega_r \) back stress acting on the slip system
- K drag stress acting on the slip system

The model has been formulated to include several effects that have been reported to influence deformation. These include contributions from slip system stresses other than the Schmid shear stress, latent hardening due to simultaneous straining on all slip systems, and cross-slip from the octahedral to the cube slip systems. A large body of isothermal constitutive data has been obtained at temperatures ranging from 427 to 1149 °C using uniaxial specimens oriented in the
of an out-of-phase thermomechanical cycle is compared. Figures 6 and 7 show the measured stress strain behavior and the calculated constitutive model behavior at 871 °C. The model is currently being evaluated against the stress-strain response of thermomechanical fatigue (TMF) tests which were conducted for life modeling. The single crystal constitutive model as well as the coating constitutive model reported below are compatible with a commercially available finite element computer code.

Pratt & Whitney coating constitutive model. Thermomechanical fatigue (TMF) cracks in turbine airfoils of PWA 1480 material generally originate from a coating layer. However, many coated non-

\[ \text{Cyclic Crack Initiation} \]

Directionally cast, anisotropic, nickel-base superalloys (particularly single crystals) exhibit greater creep-fatigue resistance than their conventionally cast polycrystalline counterparts. To take full advantage of these improved material properties, however, requires the development of accurate cyclic constitutive and life prediction models for these highly directional alloys. Direct modification of polycrystalline behavior models is inadequate, and a new approach that recognizes the micromechanisms of crystal response is necessary. Unfortunately, the program was unable to address only the crack initiation aspects of single crystal superalloys. Cyclic crack growth life prediction modeling must await future efforts.

Pratt & Whitney coating and single crystal life prediction model. Generally, all coated PWA 1480 orientations (i.e., <001>, <011>, <111>, and <123>) were tested in thermomechanical fatigue initiated cracks in the metal at sites where coating cracking had occurred. Isothermal tests of coated <001> PWA 1480 also typically initiated cracks first in the coating layer. However, many coated non-<001> isothermal fatigue tests initiated cracks underneath the specimen outer surface in either the PWA 1480 or the coating/PWA 1480 interfacial region. Initiation occurred predomina

The following life prediction approach was developed to account for the observed specimen cracking modes.
Prediction of these test results should improve when 1149 °C (2100 °F) isothermal tests are included in the data set used to determine model constants.

Additional model modification will be necessary to include the effect of blaxial coating loads introduced by the thermal growth mismatch between the coating and the substrate during uniaxial TMF tests and engine transients.

PWA 273 aluminide coating and PWA 1480 crack initiation model development for calculating 

N_{sc}, N_{sp}, and N_{si} is currently in process. At present, based on isothermal fatigue correlations, the most promising candidate models for these materials are also derived from an approach based on hysteretic energy.

CONCLUDING REMARKS

In conclusion, we would like to emphasize that significant accomplishments have been achieved in the fatigue and fracture arena through the atmosphere created by the HOST Project. We are now much better able to deal with durability enhancement in the aeronautical propulsion industry through theoretical, analytical, and experimental approaches. Given the ability to complete the tasks we have started, we expect to reap even greater rewards in the near future.

The major accomplishments to date are summarized below:

1. An advanced high-temperature fatigue and structures research laboratory has been implemented at the NASA Lewis.
2. Two new crack initiation life prediction methods have been developed for application to complex creep-fatigue loading of nominally isotropic superalloys at high temperatures.
3. Cyclic constitutive models for oxidation protective coatings and for highly anisotropic single crystal turbine blade alloys have been developed and verified.
4. A preliminary cyclic crack initiation life prediction model for coated single crystal superalloys has been proposed and is undergoing continued evaluation. The model utilizes tensile hysteretic energy and frequency as primary variables.
5. Two high temperature cyclic crack growth life prediction models have been proposed: micromechanical and phenomenological engineering approaches have been taken. The micromechanical approach is based upon oxidation interactions with mechanical deformation at the crack tip, while the engineering approach has its origins in the use of Path-Independent Integrals to describe the necessary fracture mechanics parameters.

REFERENCES


**TABLE I. - HOST FATIGUE AND FRACTURE PROGRAMS**

- NAS3-23288, Pratt & Whitney (R.S. Nelson) Creep-Fatigue Crack Initiation--Isotropic
- NAS3-23940, General Electric (J.J. Laflen) Elevated Temperature Crack Growth--Isotropic
- NAS3-23939, Pratt & Whitney (G.A. Swanson) Life Prediction/Constitutive Modeling--Anisotropic
- NAG3-348, Syracuse University (H.W. Liu) Crack Growth Mechanisms--Isotropic
- Lewis (M.A. McGaw) High-Temperature Fatigue and Structures Laboratory
OUT-OF-PHASE
IN-PHASE
CW ELLIPTICAL
CCW ELLIPTICAL
DOGLEG
HIGH TEMPERATURE

Figure 1. Application of preliminary CDA model to TMF life prediction for the cast nickel-base alloy, PWA 1455 (B1900 + Hf), after Moreno (1986).

Figure 2. Schematic representation of total strain-strainrange partitioning (TS-SRP).

104
100 000

10 000

1000

100

10

ACTUAL LIFE, CYCLES

PREDICTED LIFE, CYCLES

○ 1600 °F, 0.5%, R = 0, 0.5 CPM (SERIES 1)
□ 1600 °F, 0.5%, R = 0, TENS HOLD (SERIES 2)
◊ 1600 °F, 0.75 ksi LOAD CONTROLLED (SERIES 3)
△ 1800 °F, 0.75%, THEN 0.25-0.75%, 10 CPM (SERIES 4)
▲ 1800 °F, 0.5%, R = 0, 1 CPM (SERIES 5)

871 °C (1600 °F)
983 °C (1800 °F)


STRESS = 10 ksi

650 °C

0.25 CM THICK

PATH NUMBER

538 °C

1.0 CM

J-RICE (1968)

J-KISHIMOTO (1980)

J-AINSWORTH (1978)

J-BLACKBURN (1977)

TADA (1973)

1.5

1.0

0.5

0

1

2

3

4

5

INTEGRATION PATH NUMBER

**MATERIAL TEMPERATURE, $\Delta K$(MPA $\sqrt{m}$) WAVE-FORM \(^\circ\text{C}\)**

- Inconel 718 649 28
- Inconel X-750 650 30
- Inconel X-750 650 30
- Astroloy 760 50
- Astroloy 650 50
- 304 S.S. 538 30
- Waspaloy 649 30
- 1/2 Cr-Mo-V Steel 565 10
- 2 1/4 Cr-Mo Steel 565 10

**FIGURE 5. - EVALUATION OF THE MICROMECHANISTIC OXIDATION CRACK EXTENSION MODEL OF LIU AND OSHIDA (1986).**

**FIGURE 6. - EXPERIMENTAL LOOPS IN \((111)\) AND \((001)\) DIRECTIONS AT 871 \(^\circ\text{C}\) (1600 \(^\circ\text{F}\)) AT STRAIN RATES OF: (A) 0.001% PER SECOND, (B) 0.0025% PER SECOND, (C) 0.01% PER SECOND, (D) 0.1% PER SECOND, AND (E) 0.5% PER SECOND.**

**FIGURE 7. - MICRO MODEL WITH BOTH OCTAHEDRAL AND CUBE SLIP TERMS CORRELATED TO \((111)\) AND \((001)\) DATA.**

**FIGURE 8. - OVERLAY COATING CONSTITUTIVE MODEL PREDICTION OF THERMAL MECHANICAL CYCLE AND COMPARISON WITH DATA.**
FIGURE 9. - OVERLAY COATING LIFE MODEL CORRELATION OF ISOTHERMAL LIFE DATA AND PREDICTION OF THERMAL MECHANICAL FATIGUE LIFE DATA.