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APPLICATION OF CYCLIC DAMAGE ACCUMULATION LIFE PREDICTION MODEL TO HIGH TEMPERATURE COMPONENTS

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INTRODUCTION

A high temperature, low cycle fatigue life prediction method has been developed by Pratt & Whitney under the sponsorship of the Lewis Research Center (Moreno et al, 1984). This method, Cyclic Damage Accumulation, has been developed for use in predicting the crack initiation lifetime of gas turbine engine materials, but it can be applied to other materials as well. The method is designed to account for the effects on creep-fatigue life of complex loadings such as thermomechanical fatigue, hold periods, waveshapes, mean stresses, multiaxiality, cumulative damage, coatings, and environmental attack (Nelson et al, 1986). Several features of the model were developed to make it practical for application to actual component analysis, such as the ability to handle non-isothermal loadings (including TMF), arbitrary cycle paths, and multiple damage modes.

The CDA life prediction model was derived from extensive specimen tests conducted as part of the contract activity on the cast nickel-base superalloy B1900+Hf. These included both monotonic tests (tensile and creep) and strain-controlled fatigue experiments (uniaxial, biaxial, TMF, mixed creep-fatigue, and controlled mean stress). Additional specimen tests were conducted on wrought INCO 718 to verify the applicability of the final CDA model to other high-temperature alloys. The model will be available to potential users in the near future in the form of a FORTRAN-77 computer program.

FEATURES OF CDA LIFE PREDICTION MODEL

The CDA model is based on the fundamental assumption that an instantaneous damage rate can be calculated and integrated on a cycle-by-cycle basis until a damage of unity is achieved. The current constants in the program reflect the definition of damage as the initiation of detectable cracks (0.030 in. {0.76 mm.}) at the location being considered. Other definitions of damage may also be modeled by recalibration of the various constants. Different rates are calculated simultaneously for whatever modes of damage may apply to a particular material. Currently defined modes in the CDA program include transgranular and intergranular fatigue, oxidation, and coating cracking.

One of the most significant features of the CDA model is its use of ratios of stress/strain parameters rather than absolute levels. This technique greatly simplifies practical application of the model to actual

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components, since these ratios are generally easier to calculate than the absolute levels. The model also makes use of total strain rather than inelastic strain; this avoids the problem of having to calculate the very small inelastic strains associated with the typically high design lives for components made of modern superalloys. The transgranular damage model incorporates a loading history term derived from primary creep data. This captures the effects of overloads and other previous load excursions which can set up compliant dislocation structures and thereby affect subsequent fatigue behavior. Mean stress effects are handled through an exponential term based on the ratio of maximum cycle stress to a reference maximum stress. Subcycles are determined by the computer program using the traditional rainflow cycle counting method, based on reversals of stress range ratio rather than stress or strain alone.

Temperature effects are very important to any high temperature model, and these are included in the CDA transgranular model in several ways. First, time dependence (hold time, strain rate, etc.) is introduced through the use of a multiplier term based on the integral of an Arrhenius function. This will automatically handle any arbitrary periodic waveform, eliminating the need to estimate average strain rate, frequency, or other such parameters from a component loading history. Second, an additional strain term is postulated to result from microscopic thermal expansion mismatch within the material structure. This is added to the macroscopic total strain, and the resulting strain range is used by CDA to compute the life. Finally, temperature effects are included implicitly through the temperature dependence of certain reference stress/strain quantities.

The second major damage mode currently active in the CDA model is the intergranular mode. This is based on an integral of an Arrhenius function which is calibrated to data from creep testing. This was found adequate for many components which fail simply from cyclic loadings in the creep regime. Other damage modes include cyclic oxidation (which modifies the transgranular damage term) and coating cracking (based on the coating life model from a companion NASA contract {Swanson et al, 1987}).

APPLICATION TO HIGH TEMPERATURE COMPONENTS

The CDA computer program is designed to accept one or more "defined cycles" for which a complete stress/strain/temperature/time history is known. These may be obtained from several sources, including simplified methods or full inelastic analysis programs. The program accepts this data (interpolating where required) and directly integrates the rates of the various damage modes until one of them reaches unity.

REFERENCES

Moreno, V., Nissley, D. M., and Lin, L. S., 1984, "Creep Fatigue Life Prediction for Engine Hot Section Materials (Isotropic) Second Annual Report," NASA CR-174844.

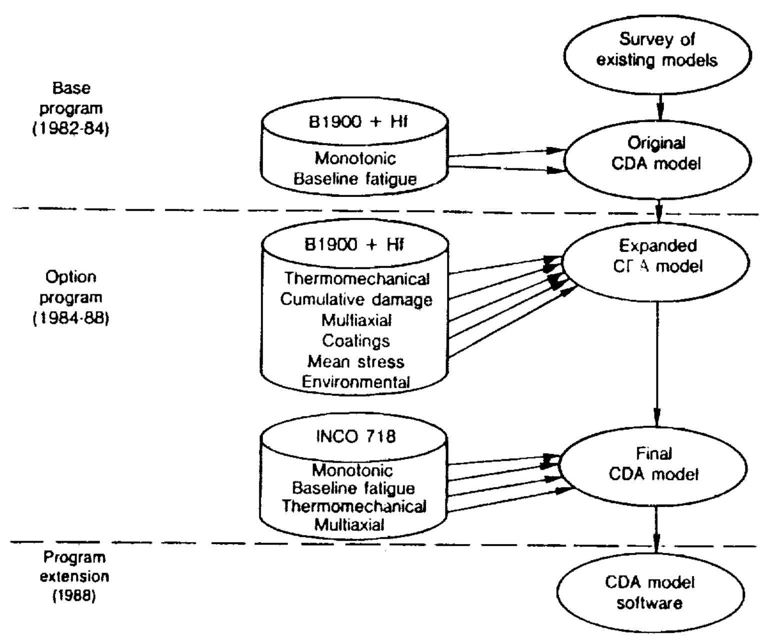
Nelson, R. S., Schoendorf, J. F., and Lin, L. S., 1986, "Creep Fatigue Life Prediction for Engine Hot Section Materials (Isotropic) Interim Report," NASA CR-179550.

Swanson, G. A., Linask, I., Nissley, D. M., Norris, P. P., Meyer, T. G., and Walker, K. P., 1987, "Life Prediction and Constitutive Models for Engine Hot Section Anisotropic Materials Program," NASA CR-179594.

OVERVIEW

- Summary of Contract Activities
- Features of CDA Life Prediction Model
- Application to High Temperature Components
- Future Research

THE CDA METHOD IS BASED ON EXTENSIVE HIGH TEMPERATURE SPECIMEN TESTING



CDA MODEL BEGINS WITH INTEGRATION OF DAMAGE RATES FOR MULTIPLE MODES

For use as a practical design method, "Damage = 1" is defined as initiation of a 0.030 in. (0.76 mm.) surface length crack

- The basic equation for CDA is simply an integration of damage rate from 0 to 1:

$$1 = \int_{1}^{Ni} \frac{dD}{dN} \, dN \quad (1)$$

- This same calculation is performed simultaneously for multiple modes of damage, as required for a given material. Currently defined modes include:

1. Transgranular fatigue
2. Intergranular fatigue
3. Oxidation / environmental damage
4. Interactions of the above

TRANSGRANULAR DAMAGE MODEL UTILIZES A STRESS AND STRAIN RATIO CONCEPT

Absolute inelastic strains can be small and difficult to predict reliably for many nickel-base superalloys

- The damage rate is calculated using the ratio of current parameters to reference values:

$$\frac{dD}{dN} = \left(\frac{1}{N_{REF}}\right) \left(\frac{\Delta\varepsilon T}{\Delta\varepsilon_{T,\ REF}}\right)^{\eta 1} \left(\frac{\Delta \sigma}{\Delta\sigma_{REF}}\right)^{\eta 2} \left(\frac{\varepsilon_{P,REF}}{\varepsilon p}\right) \quad (2)$$

- A loading history parameter derived from primary creep data is also included:

$$\left(\frac{\varepsilon p}{\varepsilon_{P,REF}}\right) = f_{\varepsilon p} \left(\frac{\sigma_{MAX}}{\sigma_{\varepsilon P,REF}}\right)_{MAX,\ HISTORY} \quad (3)$$

TWO ADDITIONAL TERMS WERE NECESSARY TO PREDICT BASELINE FAST RATE DATA

- The first predicts mean stress and R-ratio effects using a ratio based on maximum tensile stress:

$$\frac{dD}{dN}_{BASIC} = \frac{dD}{dN}\, e^{\left(\frac{\sigma_{MAX}}{\sigma_{MAX,REF}}\right)} \qquad (4)$$

- A threshold strain range was necessary to predict the high life, low strain data for both B1900+Hf and INCO 718:

$$\Delta\varepsilon_T = \Delta\varepsilon_{T_{ACTUAL}} - \Delta\varepsilon_{T_{THRESHOLD}} \qquad (5)$$

STRAIN RATE EFFECTS CAN BE PREDICTED FOR ANY ARBITRARY WAVEFORM

Permits direct application of CDA to practical component cycles

- The basic transgranular damage rate (product of the previous terms) is modified by a time & temperature dependent term:

$$f_{TD} = 1 + \int A_1 e^{B_1 \sigma} e^{-\left(\frac{Q1}{RT}\right)} dt \qquad (6)$$

- This eliminates the need to estimate hold time, average frequency, or other similar parameters for complex loading cycles typically experienced by modern high temperature components

CLASSICAL CUMULATIVE DAMAGE EFFECTS ARE ALSO PREDICTED BY THE CDA MODEL

Real components see a spectrum of loads during their service life

- Non-linear damage accumulation is included in a modifying function for the basic transgranular damage rate:

$$G(D) = (1-f_L)(\beta+1)\,D^{\beta} + f_L \qquad (7)$$

$$\text{where } \beta = \left(\frac{B_{NL}}{dD/dN_{BASIC}}\right)^{\alpha} \qquad (8)$$

- Subcycles are computed using the rainflow cycle counting method based on reversals of stress range ratio

- The primary creep ductility term automatically reduces the damage done by subcycles when their maximum stress is lower than that of the major cycle

THE RATIO CONCEPT PERMITS CDA TO HANDLE NON-ISOTHERMAL LOADING

Many practical applications involve varying temperature

- The reference stresses and strains are functions of temperature for each material in the CDA library

  This is sufficient for variable temperature components below the range where TMF is a concern

- For TMF, an additional strain due to thermal expansion coefficient mismatch was necessary to correlate the data:

$$\epsilon_{TMF} = \int_0^t \Delta\,\alpha(T)\,\dot{T}\,dt \qquad (9)$$

THE SECOND DAMAGE MODE PREDICTS INTERGRANULAR FAILURE MECHANISMS

Often components fail by cyclic loads which result in failure by creep mechanisms, not fatigue

- The damage rate for this mode is based on an Arrhenius function, but with constants which are different from those used for the transgranular mode:

$$\frac{dD}{dN} = \int A_2\, e^{B2\,\sigma} e^{-\left(\frac{Q2}{RT}\right)} dt \qquad (10)$$

- This rate is integrated cycle-by-cycle along with the transgranular damage rate (and any other active modes) until some mode reaches a value of unity

ENVIRONMENTAL DAMAGE CAN BE INCLUDED FOR CYCLIC AND STATIC OXIDATION

Certain components can switch between these modes, depending on how they are operated

- For cyclic oxidation, a multiplier factor based on a time-temperature dependent integral is added to the transgranular damage model

- For static oxidation, a separate third damage mode can be calculated which depends only on time and temperature, not cyclic variables such as stress or strain

INTERACTIONS BETWEEN DAMAGE MODES CAN BE EASILY INCORPORATED

- Where interactions are observed among the various damage modes (creep/fatigue/environment), these are handled by combining damage levels from those modes and integrating the result as a separate mode
- Almost any type of interaction may be modeled using this technique:

1. Linear (additive)
2. Non-linear
3. Power law

COATING LIFE PREDICTIONS UTILIZE THE MODEL FROM A COMPANION CONTRACT

Many modern superalloys must be coated for oxidation protection in actual service; this must be accounted for by a practical system

- First, a viscoplastic constitutive model is used to predict the local stress/strain history in the coating itself
- This coating stress/strain history is next used to predict coating cracking life (through the coating thickness)
- Finally, this life is converted to an equivalent damage rate which can be integrated along with the other active damage modes for the substrate material

MULTIAXIAL STRESS/STRAIN STATES ARE CONVERTED TO EQUIVALENT CDA VALUES

Many actual components are analyzed using 3-D methods which produce full tensors; these must be interpreted by a practical life system

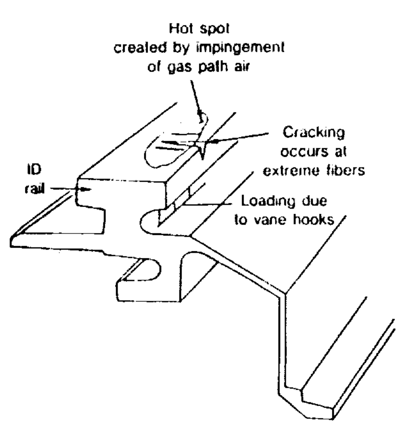
- The applied stress/strain tensors are transformed into 100 different axis orientations in the plane of the component surface to search for the crack plane (with the "worst" orientation)

- Two different algorithms are currently implemented for choosing the plane which experiences the worst damage:

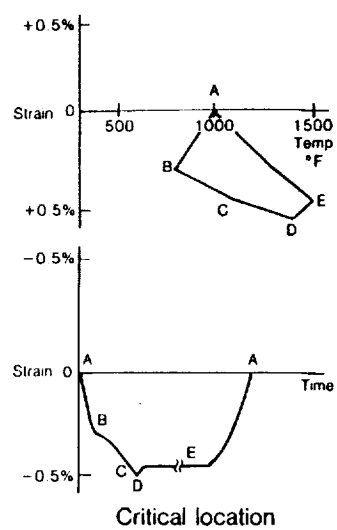
  1. Maximum normal strain range
  2. Socie parameter (combination of shear and normal)

- New materials may use these or choose some other appropriate parameter

THE EFFECTS OF COMPLEX STRAIN AND TEMPERATURE HISTORIES MUST BE DETERMINED FOR ACCURATE LIFE PREDICTIONS



Outer vane support
TMF crack location



Critical location
strain-temp-time histories

CDA USES THE GIVEN STRESS/STRAIN HISTORY DIRECTLY TO PREDICT LIFE

- The CDA program accepts as input one or many "defined cycles" for which a full stress/strain history is known. These may come from many sources:

  1. Actual rig data taken during specimen testing
  2. Simplified methods using elastic input
     a. Neuber's rule
     b. Integrated energy density
  3. Full inelastic analysis methods
     a. Finite element
     b. Boundary integral equation

- The program performs semi-log interpolation of damage rates to determine intermediate values between the defined cycles

THE CDA PROGRAM CAN BE EASILY EXPANDED FOR NEW MATERIALS OR METHODS

"The only thing constant is change ..."

- The current CDA equations are sufficient for most current nickel-base alloys; a new set of constants can be generated for materials other than B1900+Hf or INCO 718

- The program is modular so that new equations, damage modes, or even completely different life prediction methods can be added if desired

- The program is written in standard FORTRAN-77 and has run on machines from PC's to mainframes; source code will be available for distribution soon

FUTURE RESEARCH

Practical methods must undergo continuous improvement and continue to adapt to new materials and analytical methods

- The extensive database for B1900+Hf, including both constitutive and creep-fatigue data, provides an excellent opportunity for evaluating new prediction methods

- TMF cycle path effects (such as CW vs. CCW elliptical cycles) are not fully explained by the current CDA formulation; possible new methods include:

  1. Equilibrium stress/strain methods
  2. Micromechanical models

- The CDA model could be applied to the constituent materials in advanced systems such as metal matrix composites