CREEP FATIGUE LIFE PREDICTION FOR ENGINE HOT SECTION MATERIALS (ISOTROPIC) - THIRD YEAR PROGRESS REVIEW[1]

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INTRODUCTION

As gas turbine technology continues to advance, the need for advanced life prediction methods for hot section components is becoming more and more evident. The complex local strain and temperature histories at critical locations must be accurately interpreted to account for the effects of various damage mechanisms such as fatigue, creep, and oxidation and their possible interactions. As part of the overall NASA HOST effort, this program is designed to investigate these fundamental damage processes, identify modeling strategies, and develop practical models which can be used to guide the early design and development of new engines and to increase the durability of existing engines.

This contract is a 5-year effort comprising a 2-year base program and a 3-year option program, involving two different isotropic materials as well as two protective coating systems. The base program, which was completed during 1984, included comparison and evaluation of several popular high-temperature life prediction approaches as applied to continuously cycled isothermal specimen tests. The option program, of which one year has been completed, is designed to develop models which can account for complex cycles and loadings, such as thermomechanical cycling, cumulative damage, multiaxial stress/strain states, and environmental effects.

REVIEW OF PROGRESS DURING BASE PROGRAM

Approximately 150 tensile, creep, and fatigue tests were conducted during the base program using specimens made from a single heat of cast B1900+Hf material. The fatigue tests were conducted in an axial strain-controlled mode at temperatures between 538°C (1000°F) and 982°C (1800°F). Initiation life was considered to be more significant than separation life; this was defined to be the cycle at which a 0.75 cm (0.030 in.) surface crack had developed, as determined by replication of selected specimens at each test condition. These tests investigated the effects on initiation of strain range, strain rate, mean strain, and compressive and tensile dwell periods.

The base program also included a review of many different life prediction methodologies, such as correlation of macroscopic parameters (strain range, mean stress), strain range partitioning (ref. 1), rate-sensitive models (Majumdar, ref. 2), work-based models (Ostergren, ref. 3), damage accumulation (ductility exhaustion), and fracture mechanics approaches. Both desirable and undesirable features of each of these were identified and used to guide the selection of the approach having the best combination of accurate predictive capability and practical specimen data requirements. The damage model which was finally chosen and developed is based on the ductility exhaustion concept and is known as the Cyclic Damage Accumulation model. Application of this model to the data generated in the base program testing

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showed very good correlation. A full description of all testing and model development conducted under the base program is contained in the second annual report (ref. 4).

THERMOMECHANICAL MODEL DEVELOPMENT

A significant task under the option program is the development of a damage model which is valid under conditions of thermomechanical fatigue (TMF). A total of 21 TMF specimen tests has been completed so far, covering variables such as strain range, temperature range, mean strain, cycle type, and hold times. A schematic comparison of some of the strain-temperature cycles used for these tests is shown in figure 1. It can be seen that the "dogleg" tests are identical to the base program isothermal hold tests, except that the temperature was not held constant during the strain holds. In general, the results of these specimen tests have demonstrated that TMF damage cannot always be predicted in the same manner used for isothermal tests; the model chosen must be sensitive to accumulation of damage from several different sources throughout the cycle.

The isothermal CDA model developed during the base program was applied to a selected group of the TMF specimen tests, using a rate of fatigue damage accumulation consistent with the highest temperature seen by the specimen during the test. The resulting predictions for the out-of-phase tests are shown in figure 2; note that the trend of the data is correctly predicted, but that the predictions are conservative. The same method was applied to the data from the in-phase and dogleg tests in this group, and figure 3 shows that, for these tests, the isothermal damage method does not predict the trends in the observed specimen initiation lives. Work is now continuing on a differential form of the CDA model in which the damage rate is variable and can be integrated around any arbitrary TMF cycle.

MULTIAXIAL STRESS STATE MODEL

Multiaxial fatigue tests are now being conducted using tubular specimens subjected to torsional loading in combination with uniaxial tension loading. Considerable effort was expended on development of the specimen, test rig and computer software codes. Collet-type grips were incorporated into the test rig to reduce the fixturing complexity and allow relaxed tolerances on the specimen grip ends which resulted in lower cost specimens.

A literature survey was conducted to identify viable approaches to predicting multiaxial effects in hot section components. Evaluation of the approaches was based on the following criteria: a demonstrated capability to predict non-proportional loading effects, use of two or more parameters to characterize multiaxial fatigue behavior, requirement for a minimal amount of multiaxial test data, and compatibility with the Cyclic Damage Accumulation model. The plastic work (ref. 5) and critical plane (ref. 6) theories were identified as having the greatest potential.

CUMULATIVE LOADING MODEL

During the tests conducted as part of this task, specimens have been exposed to mixed loading conditions to provide information regarding the interaction of different types of damage processes. A total of 44 such tests have been completed, including block tests (one set of conditions for the first block of cycles, followed by a second set of conditions for the remainder), sequenced tests (alternating blocks of two different sets of conditions), and interrupted tests (fatigue cycling interrupted by periods of temperature exposure, either with or without load). The results of these tests show that some conditions obey a linear damage rule, while certain other conditions show a strong non-linear interaction. For example, figure 4 shows an interaction diagram for the block tests run with various combinations of R-ratios, and it can be seen that running a specimen at R=0 for only a fraction of the initiation life at that condition will dramatically affect the life remaining under subsequent cycling at R=-1.

As a result of these tests, it has become clear that the CDA model must be allowed to track different cyclic ductility capabilities in each portion of a test. Also, it was observed during certain tests (such as the temperature block tests) that the damage accumulation is non-linear. These changes have been incorporated into the CDA equation through the use of the concept of ductility fraction, which is defined as the fraction of the available ductility which has been consumed:

$$\text{Ductility Fraction, } f_\epsilon = \frac{\text{Ductility Exhausted}}{\text{Available Ductility}}$$

The equation used to calculate this quantity may be written as follows:

$$f_\epsilon = \int_0^N \left(\frac{1}{\bar{\epsilon}p}\right) \left(\left.\frac{dD}{dN}\right]_{Ref}\right) F(\sigma_T, \Delta\sigma)\, dN \tag{1}$$

where:

$$F\,(\sigma_T, \Delta\sigma) = \left(\frac{\sigma T}{\sigma_{TR}}\right) \left(\frac{\Delta\sigma}{\Delta\sigma_R}\right) + \left[\left(\frac{\Delta\sigma R}{\Delta\sigma}\right)\left(\frac{\sigma T}{\sigma_{TR}}\right)\right]^{B'} \left[\left(\frac{t}{tr}\right)^{C'} - 1\right]$$

$\bar{\epsilon}_p$	grain cyclic capability for specific test condition being predicted
dD/dN_R	damage rate from fully reversed testing
$\Delta\sigma$	stress range
σ_T	maximum tensile stress
t	1/2 cycle period
R	reference condition
B',C'	constants determined from monotonic creep tests

It can be seen that when f_ϵ reaches 1, N will equal the predicted initiation life, Ni. Note also that the current initial ductility is now inside the integral, which permits the algorithm to switch from one loading condition to another which has a different initial ductility.

We may also rewrite equation 1 to perform the integration over f_ϵ instead of N, and at the same time introduce a non-linear function G(N/Ni) which has the property that its integral over the interval from 0 to 1 is always 1, no matter what values are chosen for its constants:

$$N_i = \int_0^1 \left[\frac{\bar{\epsilon}_p}{\left(\left[\frac{dD}{dN}\right]_{Ref} \right) F\left(\sigma_T, \Delta\sigma\right)} \right] G\left(\frac{N}{N_i}\right) df_e \qquad (2)$$

Several forms of the function G(N/Ni) have been evaluated, including linear and power law functions. Figure 5 shows the effect of non-linear damage accumulation on the CDA life predictions for the block loading tests, and it can be seen that in almost every case the non-linear life prediction is more accurate.

FUTURE TASKS

One of the important tasks to be completed in the near future is the investigation of the effects of environment on the fatigue process. Current plans call for screening tests in two types of atmospheres, inert (argon) and aggressive (high pressure oxygen), followed by further detailed tests in the environment which shows the greater effect. Other tasks include development of a life model for coated materials under creep-fatigue conditions and further investigation of the effects of mean stress on fatigue. The final task under the contract will be the application of the fully developed life prediction models to an alternative material and coating system in order to verify their applicability to alloys other than B1900+Hf.

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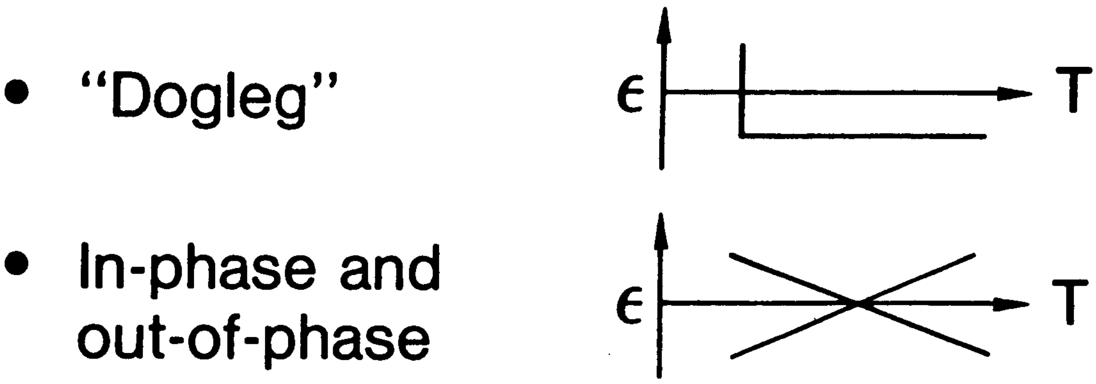

Figure 1 TMF Loading Cycles for Initial CDA Evaluation

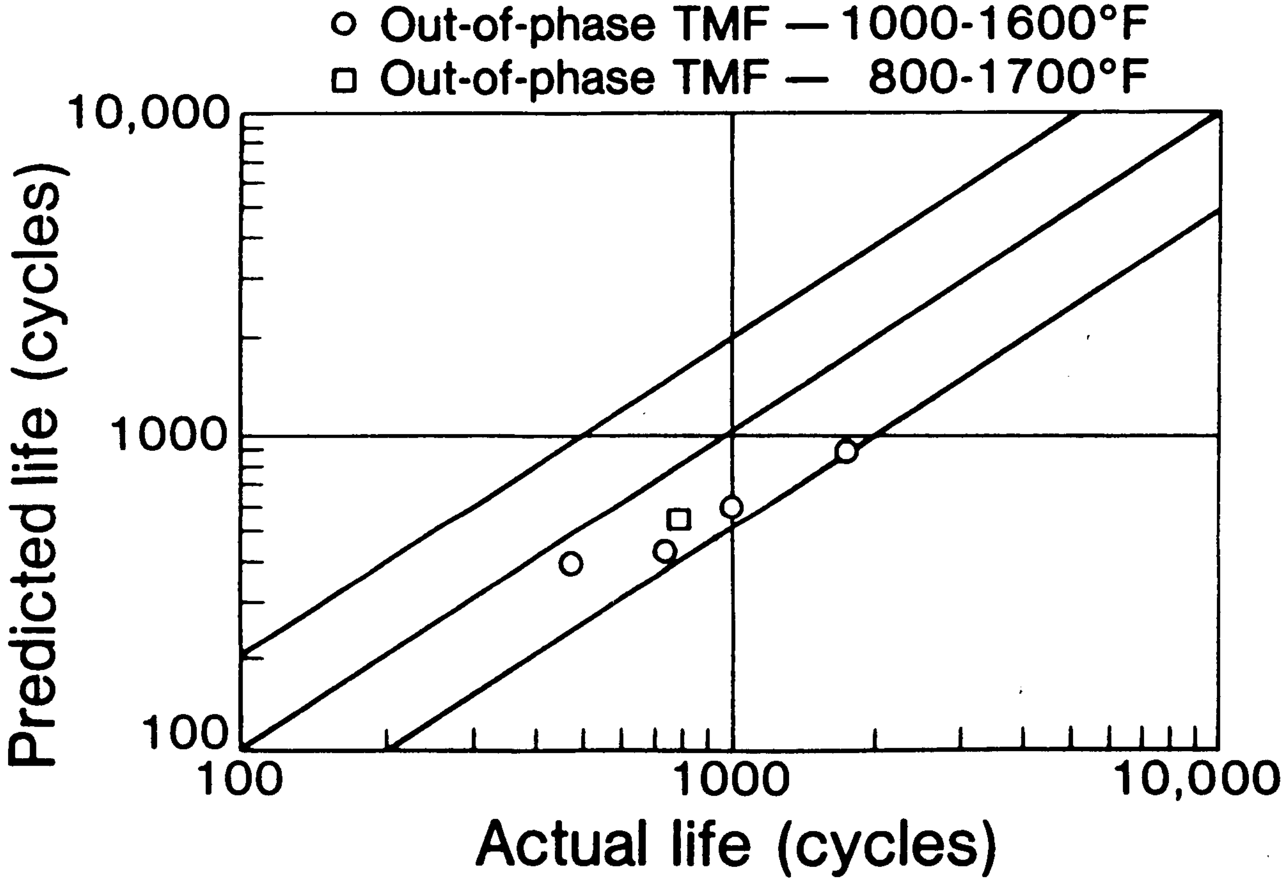

Figure 2 Prediction of Out-of-Phase TMF by CDA Model

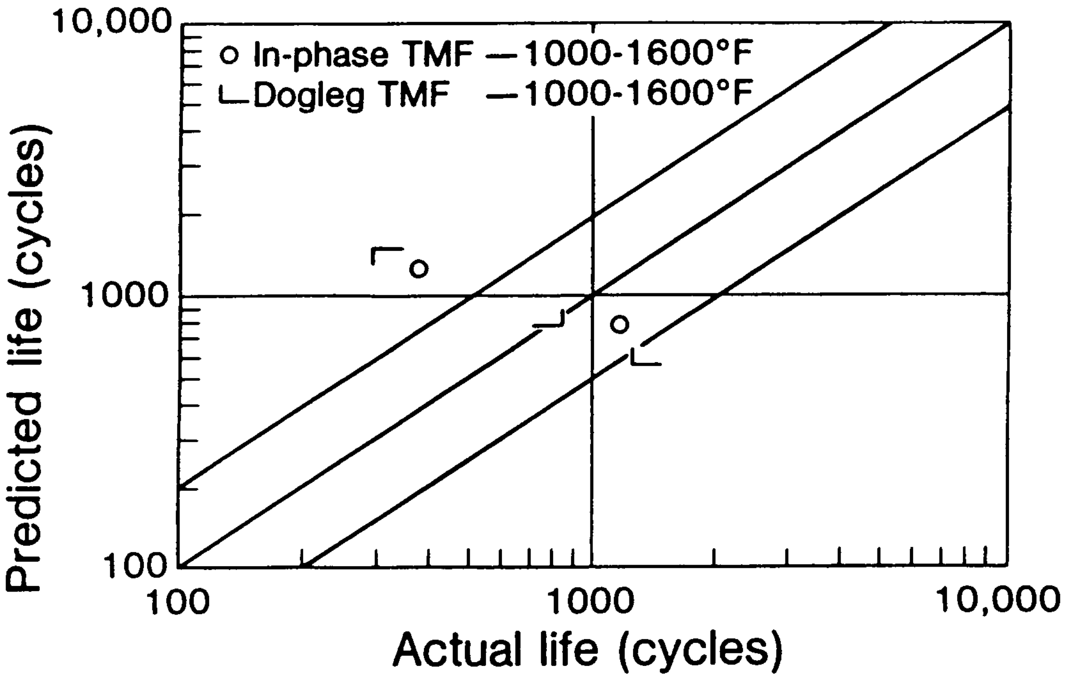

Figure 3 Prediction of In-Phase and Dogleg TMF by CDA Model

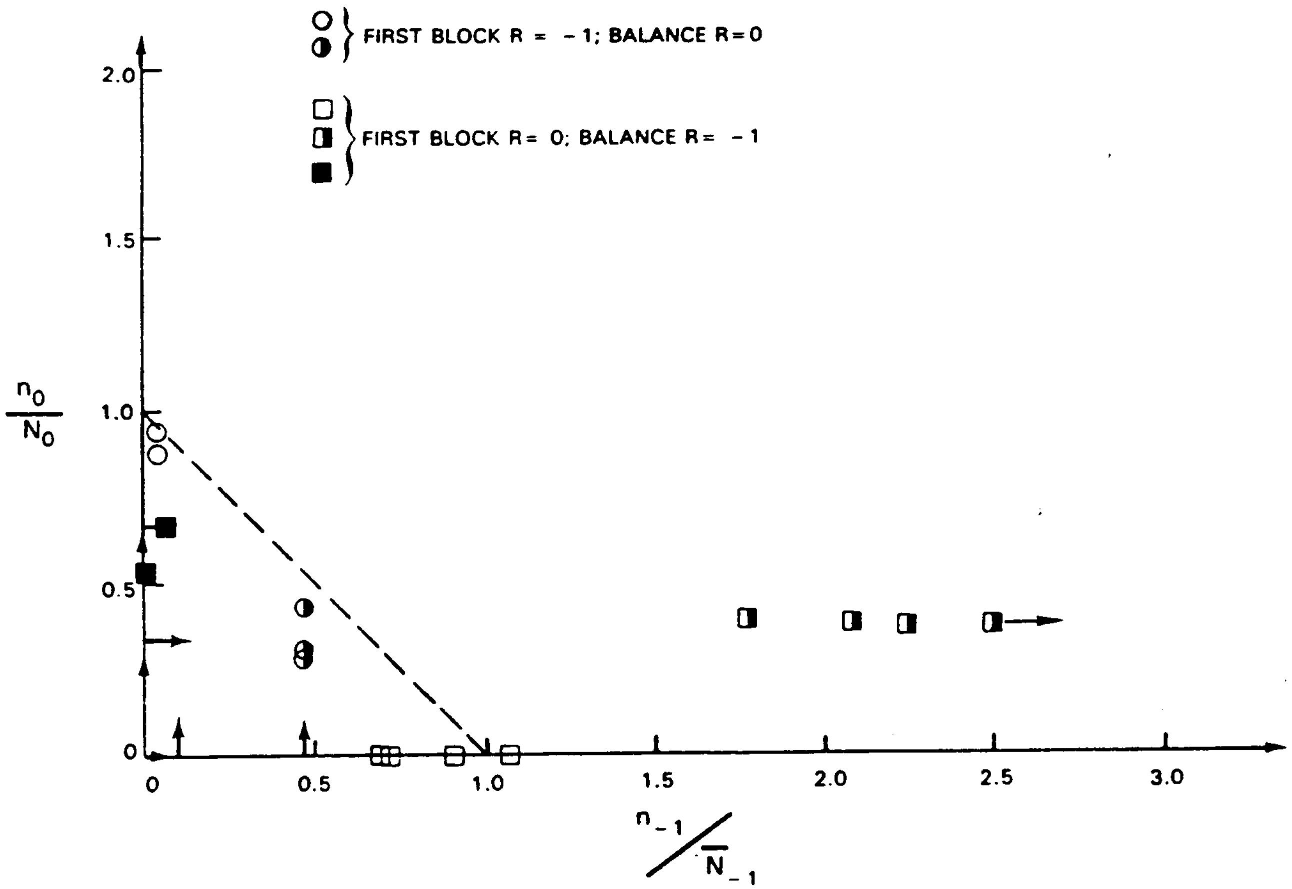

Figure 4 Interaction Diagram - Mean Stress Effects During Block Tests

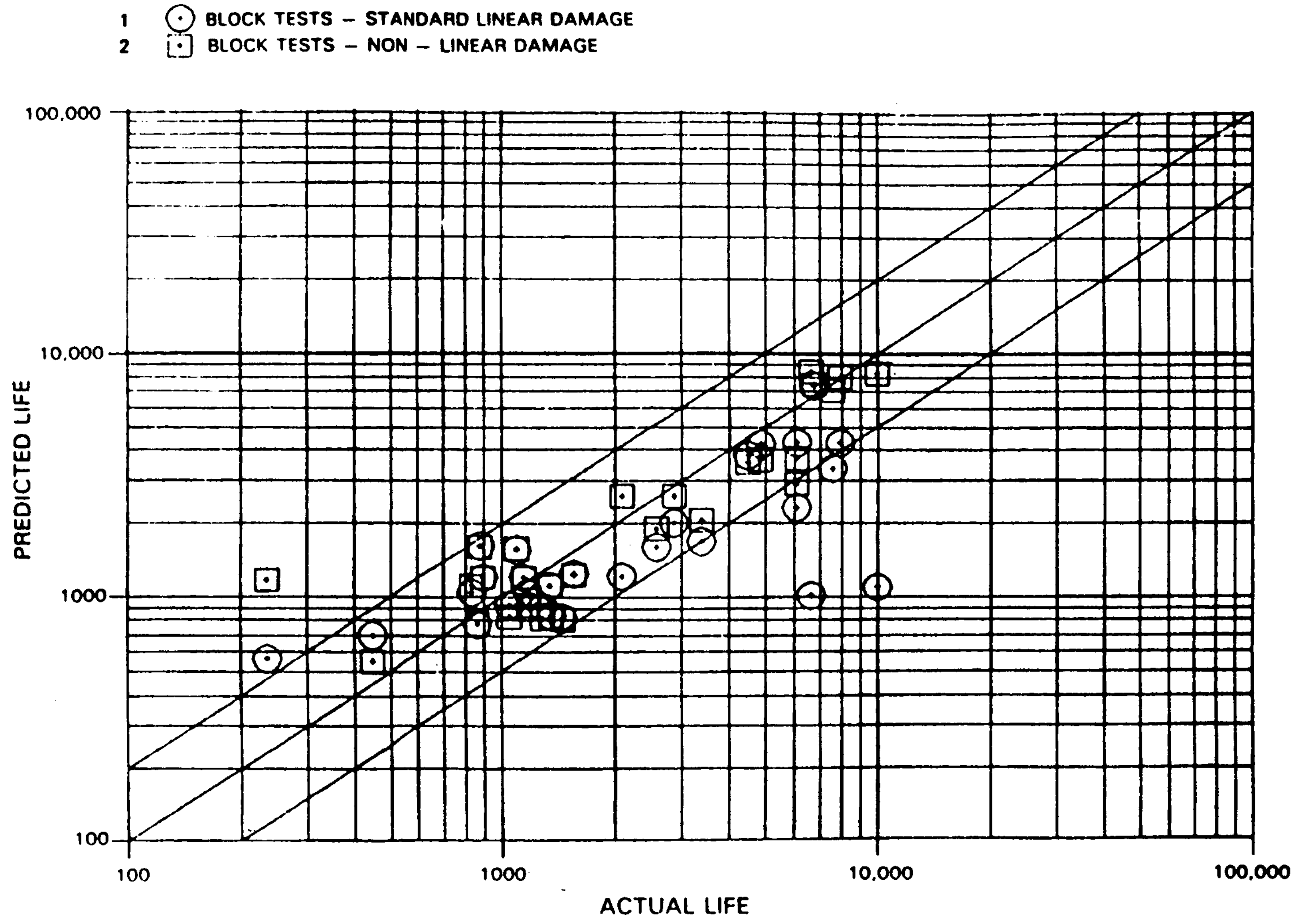

Figure 5 Effects of Non-Linear Damage Accumulation