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CREEP FATIGUE LIFE PREDICTION FOR ENGINE HOT SECTION MATERIALS (ISOTROPIC) - TWO YEAR UPDATE[1]

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INTRODUCTION

Requirements for increased durability of gas turbine hot section components have placed a greater degree of importance on accurate structural analysis and life prediction. The development of improved life prediction technology for structures operating at elevated temperatures is one of the objectives of the NASA Hot Section Technology (HOST) program. As part of HOST, the current contract will investigate fundamental approaches to high temperature life prediction, identify modeling strategies and develop specific models for component relevant loading conditions.

This contract is a 5-year, 2-part effort (2-year base program, plus a 3-year optional program) and includes two isotropic hot section materials and protective coating systems. The recently completed base program concentrated on the investigation of various life prediction approaches for high temperature applications and the selection and development of basic models for simple-cycle, isothermal loading conditions. The optional program will consider the development of models to address thermo-mechanical cycling, multi-axial conditions, cumulative loading, environmental effects and cyclic mean stress. Verification tests of models on an alternate material and coating system will also be conducted.

TECHNICAL PROGRESS SUMMARY

Base Program Material and Testing

Monotonic tensile, creep, and cyclic fatigue tests were conducted on specimens fabricated from a single heat of cast B1900+Hf material. Casting parameters were selected to produce a small, uniform grain size of approximately 0.018 cm (0.007 in.) to 0.025 cm (0.010 in.) throughout the test specimen gage sections to provide an isotropic nature to the crack initiation process. The fatigue tests were conducted in an axial strain-controlled mode at temperatures between 538°C (1000°F) and 982°C (1800°F). These tests investigated effects on initiation life of strain range, strain rate, mean strain, and compressive and tensile strain dwell periods. In all tests, crack initiation was defined as the occurrence of a 0.075 cm (0.30 in.) surface crack, as determined by replication. A total of approximately 150 tests were run in the base program.

[1]NASA Contract NAS3-23288.

Screening of Candidate Life Prediction Approaches

During the base program, various life prediction approaches were reviewed to assess their accuracy and practicality for elevated temperature life prediction. Approaches and representative models included correlation of macroscopic parameters (strain range, mean stress, etc.), inelastic strain (SRP), strain rate (Majumdar, ref. 1), work (Ostergren, ref. 2), damage accumulation (ductility exhaustion) and fracture mechanics models. The following observations were made:

1. A "ductility exhaustion" format provides a workable means of incorporating the most desirable features of the models reviewed.

   (a) The ductility can be considered a loading history-dependent parameter. This allows prediction of loading path effects, such as mean strain or overload, without including this data in the base regression for the model constants. Separate ductilities can be estimated for the grain and the grain boundaries to potentially include the mode of initiation (transgranular versus intergranular) in the prediction.

   (b) The damage (ductility exhaustion) parameter can be formulated to include time-independent and time-dependent components. For the B1900 + Hf fatigue tests conducted in this program, the two-damage components provided an improvement in the predictive capability for a range of strain rates and hold times as compared to a single-damage parameter formulation.

   (c) The required information to determine the specific damage parameter of a loading cycle is obtained from rapid cycle fatigue testing, the stress response of the cycle being predicted, and the cycle period (time).

2. Less desirable features of other models limited their applicability and increased the required analytical input. Some of these features include:

   (a) Inelastic strain or strain rate (ϵ_{PL} or $\dot{\epsilon}_{PL}$) is difficult to calculate accurately and relatively small for the loading cycles considered in this program.

   (b) Use of a crack growth model to predict initiation requires small crack growth data which is relatively difficult to obtain. Furthermore, the current level of development of time-dependent inelastic crack-tip parameters (e.g. J, C*) is such that the prediction and application to a surface-initiated crack under complex loading is not clearly defined for an immediately useable life model.

   (c) A number of the models evaluated showed good predictive capability but required various types of fatigue tests (strain rate, hold times) in the initial model data base to evaluate the necessary constants. This was considered an expensive requirement for development of a model. The applicability of the models is also limited to those materials where the data is available or planned.

From these observations, the damage model discussed below is considered as the approach having the greatest predictive capability with the most practical data base requirements. It becomes a good starting point for the additional loading cycles to be considered in the optional program.

Fatigue Model Development and Evaluation

The proposed model assumes that fatigue cracks are initiated when a measure of the grain cyclic capability is exhausted by the cycle damage and is expressed as:

$$\left|\frac{\text{GRAIN CYCLIC DAMAGE}}{\text{CAPABILITY (DUCTILITY)}}\right| - \left|\frac{\text{DAMAGE}}{\text{CYCLE}}\right| \times \text{CYCLES} = 0 \tag{1}$$

The grain cyclic ductility is determined at higher temperatures (>760°C (>1400°F)) as the amount of primary creep strain that could have been generated if the maximum stress on the first loading cycle was held constant. At lower temperatures, the cyclic ductility is determined as the amount of tensile elongation. The cycle damage function is determined as the product of a reference damage rate, (from fully reversed tests) and the ratios of tensile stress, stress range and period.

Assuming that the cycle damage is composed of time-independent and time-dependent components, the equation for initiation is written as:

$$\bar{\epsilon}_p - \int_0^N \frac{dD}{dN_R} \left\{ \left(\frac{\sigma_T}{\sigma_{TR}}\right)\left(\frac{\Delta\sigma}{\Delta\sigma_R}\right) + \left[\left(\frac{\Delta\sigma_R}{\Delta\sigma}\right)\left(\frac{\sigma_T}{\sigma_{TR}}\right)\right]^b * \left[\left(\frac{t}{t_R}\right)^c - 1\right] \right\} dN = 0 \tag{2}$$

Where:

$\bar{\epsilon}_p$	$\equiv$	grain cyclic capability for specific test condition being predicted
dD/dN_R	$\equiv$	damage rate from fully reversed testing
$\Delta\sigma$	$\equiv$	stress range
σ_T	$\equiv$	maximum tensile stress
t	$\equiv$	1/2 cycle period
R	$\equiv$	reference condition
b_1, c	$\equiv$	constants determined from monotonic creep tests

Here the integration reflects the fact that the stress response varies during the cycling.

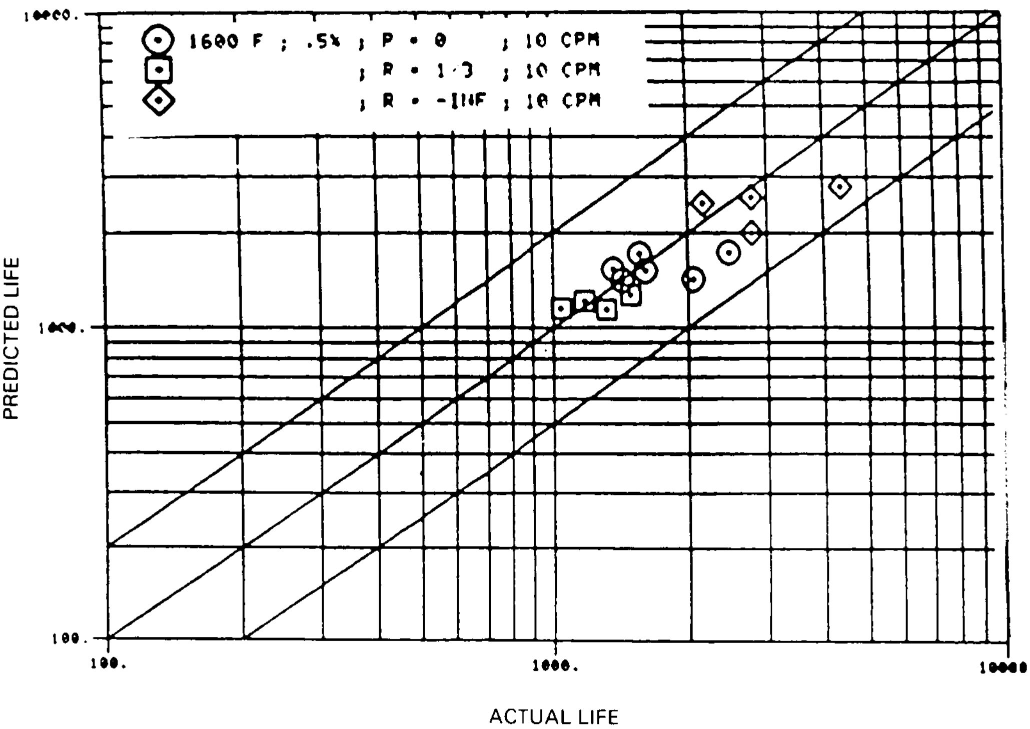
Application of equation (2) to the prediction of B1900 + Hf 871°C (1600°F) fatigue tests produced the results shown in figure 1. The prediction of rapid cycle tests at various mean strains (-0.25, +0.25, +0.50%) is shown in figure 1A. The trend of longer life with decreasing mean strain is clearly predicted. The prediction of slower strain rate and hold time tests is shown in figure 1B. The trends and the prediction in life relative to the fully reversed baseline data (not shown) are also predicted.

Prediction of mean strain and strain rate effects is also demonstrated at 537°C (1000°F) and 982°C (1800°F) in figure 2. The model predicts the reduction in life associated with a positive mean strain at 537°C (1000°F) (fig. 2A). Time-dependent damage is not included, so the trend in life is associated only with the time-independent term. At 982°C (1800°F) (fig. 2B) the correct trend in life at lower strain rates is also shown.

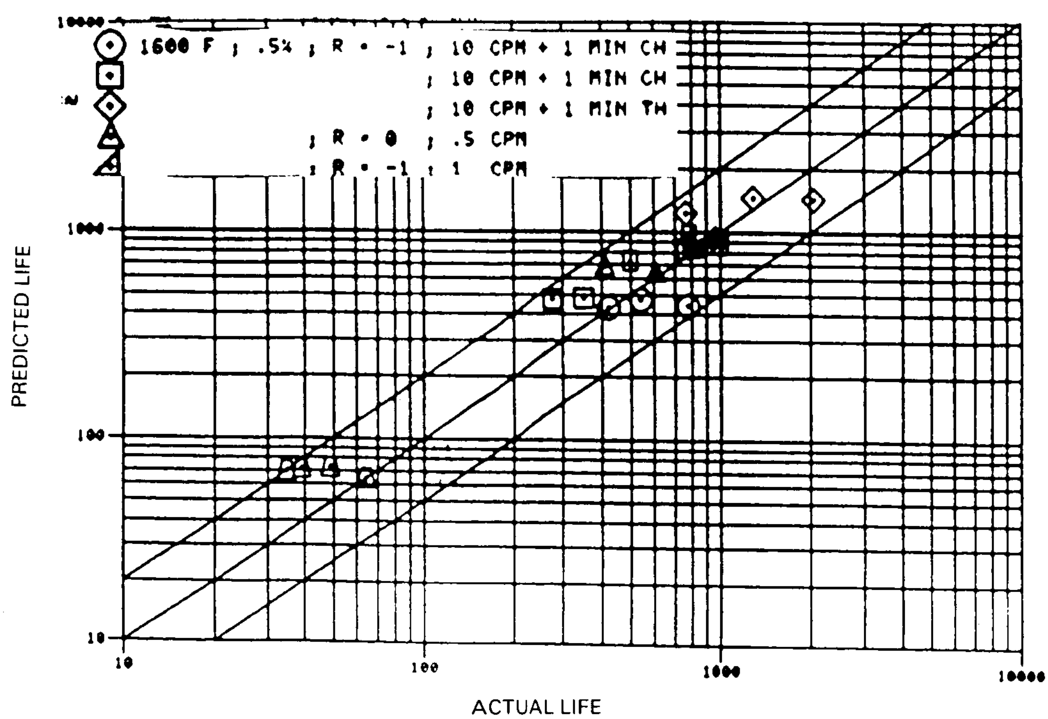
REFERENCES

1. Majumdar, S.; and Maiya, P.S.: A Mechanistic Model For Time Dependent Fatigue. Jour. of Materials & Technology. January 1980, Vol. 102, pp. 159-167.

2. Ostergren, W.J.: A General Damage Equation For Low Cycle Fatigue Life Prediction at Elevated Temperatures. Rensselaer Polytechnic Institute. Zerox University Microfilm, Ann Arbor, Mich. No. 76-27,203. 1976.



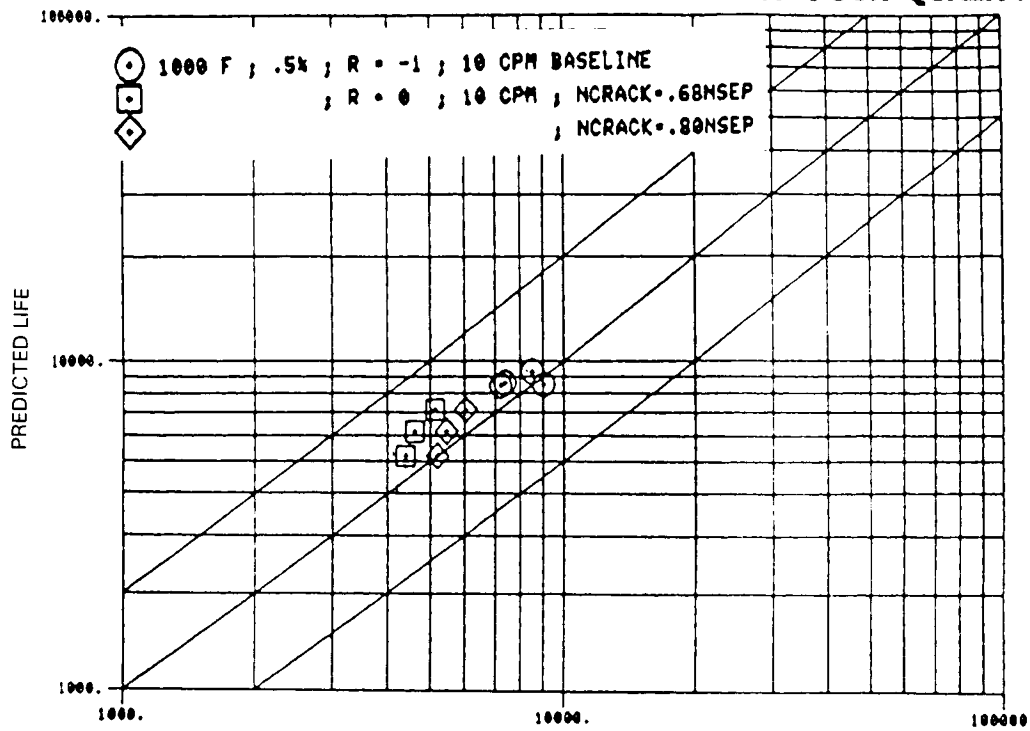
(A)



(B)

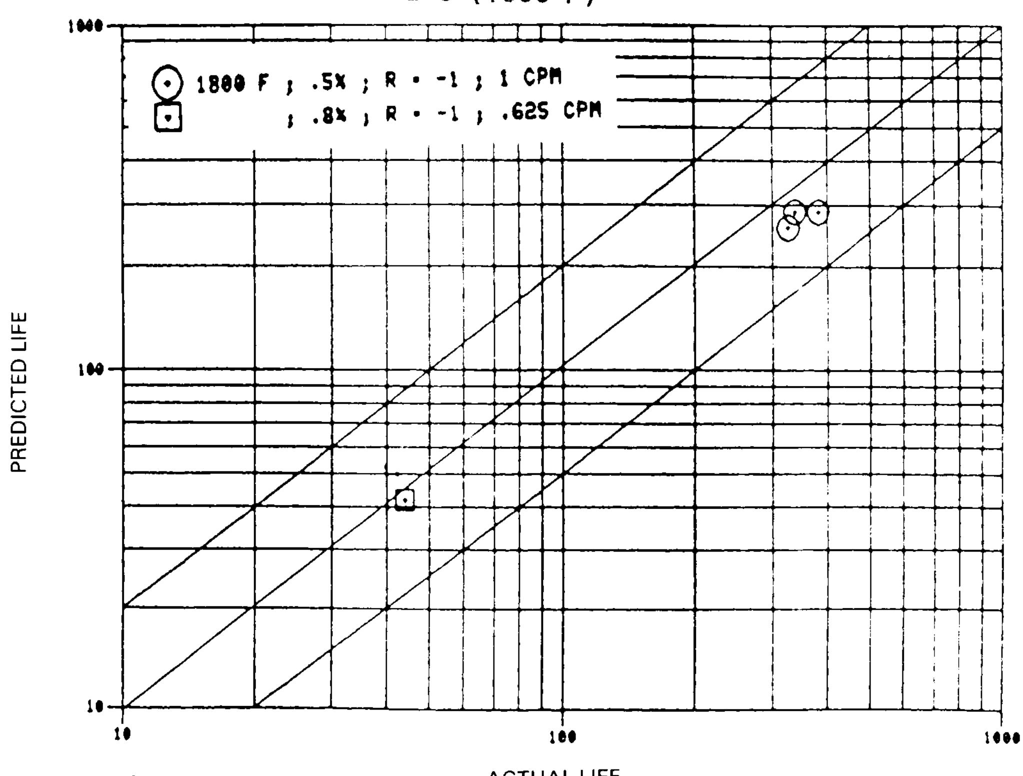
Figure 1 Mean Strain and Rate Effects Predicted at 871°C (1600°F) - Model Verification Tests

537°C (1000°F)



(A)

982°C (1800°F)



(B)

Figure 2 Similar Predictive Capability Displayed at Other Temperatures