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FATIGUE DAMAGE MODELING FOR COATED SINGLE CRYSTAL SUPERALLOYS*

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A high temperature, low-cycle fatigue life prediction method for coated single crystal nickel-base superalloys is being developed under the sponsorship of the Lewis Research Center's Gas Turbine Engine Hot Section Technology Program (HOST) by the Pratt & Whitney Division of United Technologies. The method is being developed for use in predicting the crack initiation (.010" depth in single crystal) life of coated single crystal turbine airfoils. Although the models are being developed using coated single crystal PWA 1480, they should be readily adaptable to other coated nickel-base single crystal materials. The coatings choosen for this effort were of two generic types: 1) a low pressure plasma sprayed NiCoCrAlY overlay, designated PWA 286, and 2) an aluminide diffusion, designated PWA 273 (Swanson et al., 1987).

In order to predict the useful crack initiation life of airfoils, the constitutive and failure behavior of the coating/substrate combination must be taken into account. Coatings alter the airfoil surface microstructure and are a primary source from which cracks originate (Swanson et al., 1987). The adopted life prediction approach addresses this complexity by separating the coating and single crystal crack initiation regimes. This provides a flexible means for using different life model formulations for the coating and single crystal materials. At present, the overlay coating constitutive and life models and single crystal constitutive models are available in equation form (Halford et al., 1988). Diffusion aluminide coating constitutive and life models and the single crystal life model are currently being developed.

At the completion of this program, all constitutive and life model formulations will be available in equation form and as software. The software will use the MARC general purpose finite element code to drive the constitutive models and calculate life parameters.

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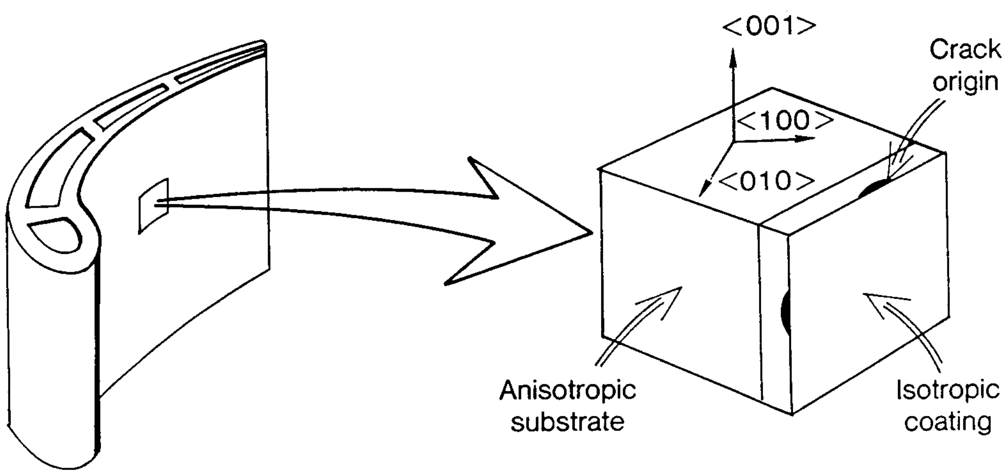
OVERVIEW

FATIGUE DAMAGE MODELING FOR COATED SINGLE CRYSTAL SUPERALLOYS

Cracking of coated single crystal airfoils is largely due to the severe thermal gradients introduced during engine transient operation. In general, oxidation/corrosion resistant coatings initiate cracks which eventually penetrate into the single crystal material thereby limiting the airfoil's useful fatigue life. This cracking behavior is modeled by considering the coating and substrate as a composite structure comprised of two materials with different constitutive and fatigue life behavior (Swanson et al., 1987; Halford et al., 1988). The effect of single crystal orientation on the constitutive and fatigue life behavior of the composite structure is included in the developed models.

NATURE OF PROBLEM

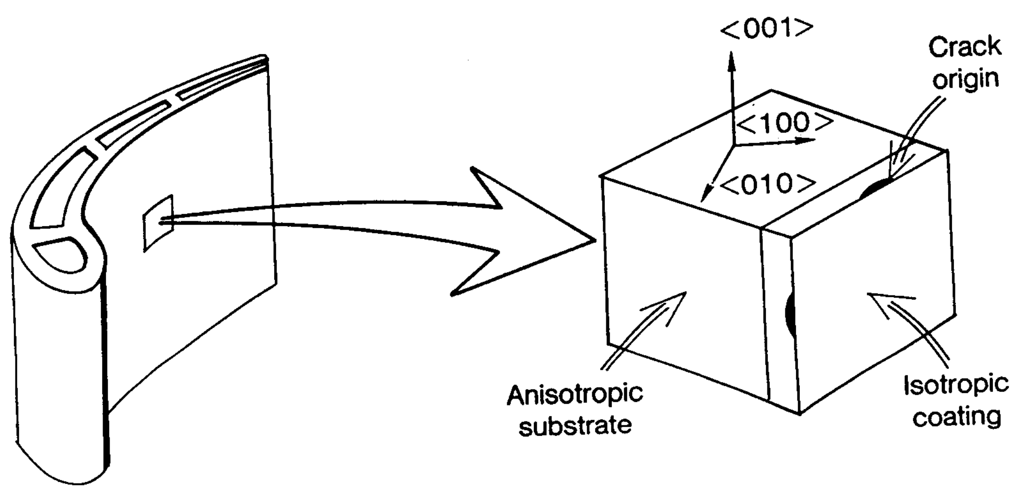
Cracking caused by thermal straining



POSTER PRESENTATION

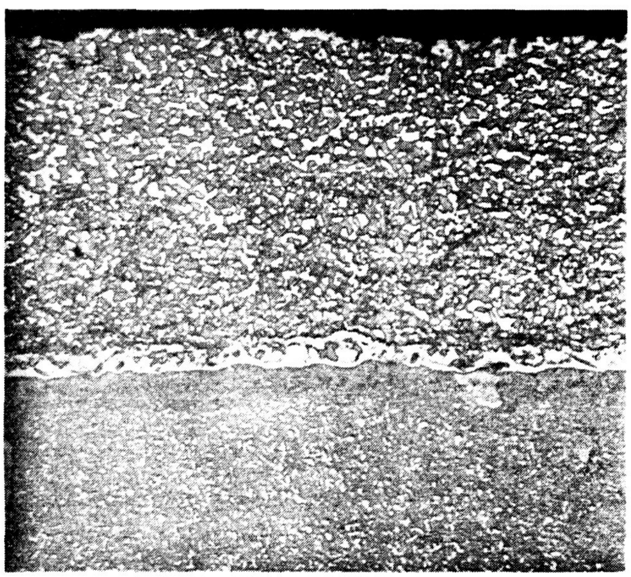
NATURE OF THE PROBLEM

This program addresses the complex cracking problem associated with coated nickel-base single crystal airfoils. It recognizes that cracking is not restricted to chordwise cracks (i.e., normal to centrifugal stress in blades), but may also occur in the spanwise direction. Since the coating is a primary crack initiation site, coating constitutive and life models must be developed as well as those for the single crystal material. Airfoil life prediction is further complicated by the fact that the fatigue life of single crystal material depends on its crystallographic orientation. All of these factors are investigated in this program.

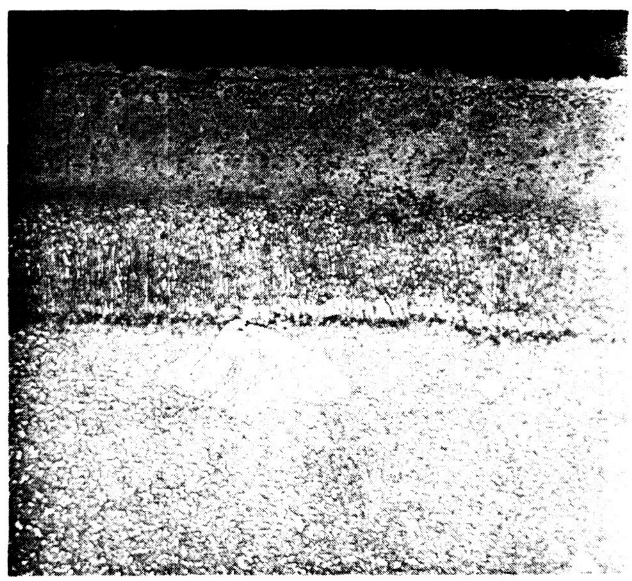


MICROSTRUCTURE OF OVERLAY AND ALUMINIDE COATINGS

Two generic coating types are being investigated: 1) PWA 286 overlay NiCoCrAlY and 2) PWA 273 aluminide. The overlay coating is applied by a low pressure plasma spray technique which produces a small diffusion zone layer and a distinct substrate/coating interface. By contrast, aluminide coatings produce a much larger diffusion zone and less distinct substrate/coating interface. The PWA 273 coating is applied by pack cementation. Both coating microstructures indicate that the coatings may be treated as isotropic for the purposes of constitutive modeling (Swanson et al., 1987). Overlay coating properties do not vary widely through the thickness so that tests of "stand-alone" coating material are useful for obtaining constitutive behavior. However, because aluminide coating properties are largely influenced by the substrate onto which it is applied, testing of a "stand-alone" aluminide coating is not possible. Unique tests useful for aluminide coating constitutive model development are described by Swanson et al. (1987).



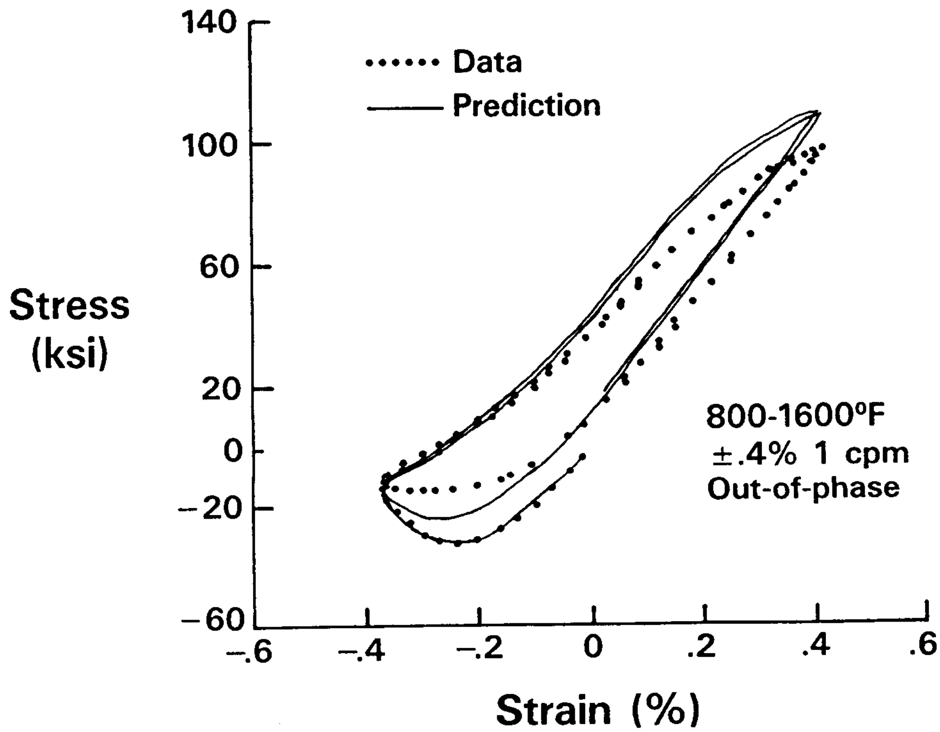
Overlay coating, PWA 286



Pack aluminide diffusion coating, PWA 273

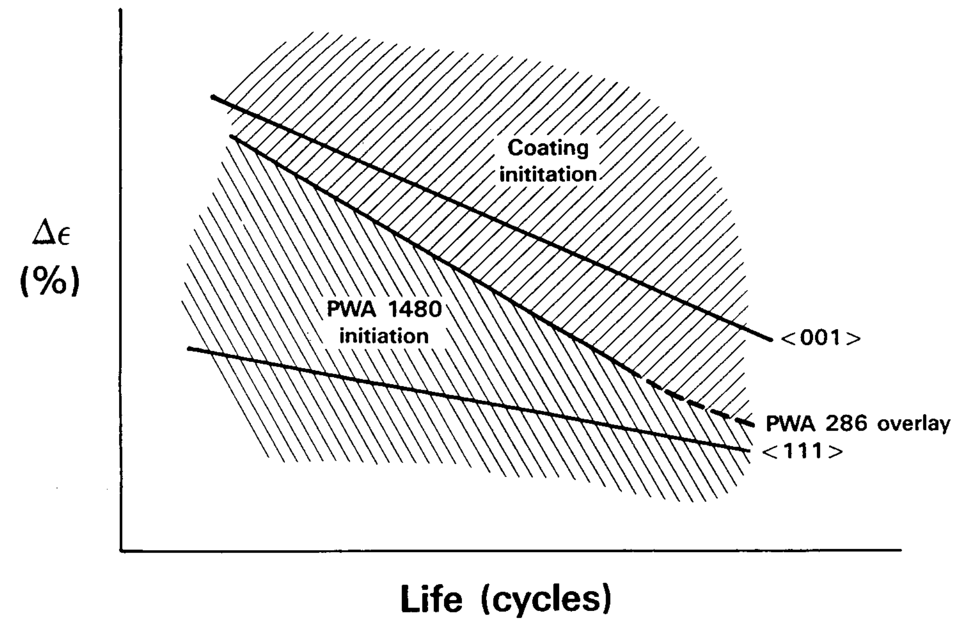
OVERLAY COATING LIFE MODEL COLLAPSES DATA WITHIN 2.5X

A modified tensile hysteretic energy life model was developed for the PWA 286 overlay coating and is reported by Halford et al. (1988). Model constants were determined from isothermal tests conducted at 427, 760, 927, and 1038C (800, 1400, 1700, and 1900F). Coating hysteresis loops were predicted using the PWA 286 overlay coating constitutive model incorporated into a two-bar mechanism. Preliminary results indicst that the model collapses a large body of isothermal and thermomechanical fatigue (TMF) life data within a factor of about 2.5. Generally, the worst predicted lives were limited to 1149C (2100F) max. temperature TMF tests. Prediction of these tests should improve when 1149C (2100F) isothermal tests are included in the data set used to determine model constants.



COMPLEX FAILURE MODES ARE OBSERVED FROM COATED SPECIMENS

The figure below schematically represents where coated PWA 1480 crack initiation occurs during isothermal fatigue. For the low elastic modulus orientation, <001>, the coating typically cracks first, but for the high modulus orientations, in this case <111>, the PWA 1480 may initiate cracks at defects, typically porosity. This represents the observed cracking at just one temperature. When the temperature is changed, the life lines tend to shift relative to one another. For example, only coating initiated cracks were observed during out-of-phase thermomechanical fatigue of both <001> and <111> orientations.



ADOPTED LIFE APPROACH REFLECTS OBSERVED CRACKING MODES

The observed specimen crack initiation modes dictated the life approach adopted for coated single crystal life prediction. The total life is considered as a sum of: 1) coating cracking, single crystal cracking (from coating cracks), and single crystal crack propagation, or 2) single crystal cracking due to discrete slip, oxidation effects, or defects (primarily porosity) and single crystal crack propagation. The obvious advantage in this approach is that life models can be individually tailored to the properties of each specific material (i.e., coating or substrate).

$$\left.\begin{aligned} N_f &= N_c + N_{sc} + N_{sp} \\ \text{or} \quad N_f &= N_{si} + N_{sp} \end{aligned}\right] \text{ whichever is smaller}$$

where: N_c = Cycles to initiate a crack through the coating.

N_{sc} = Cycles for coating crack to penetrate a small distance (.010") into the substrate.

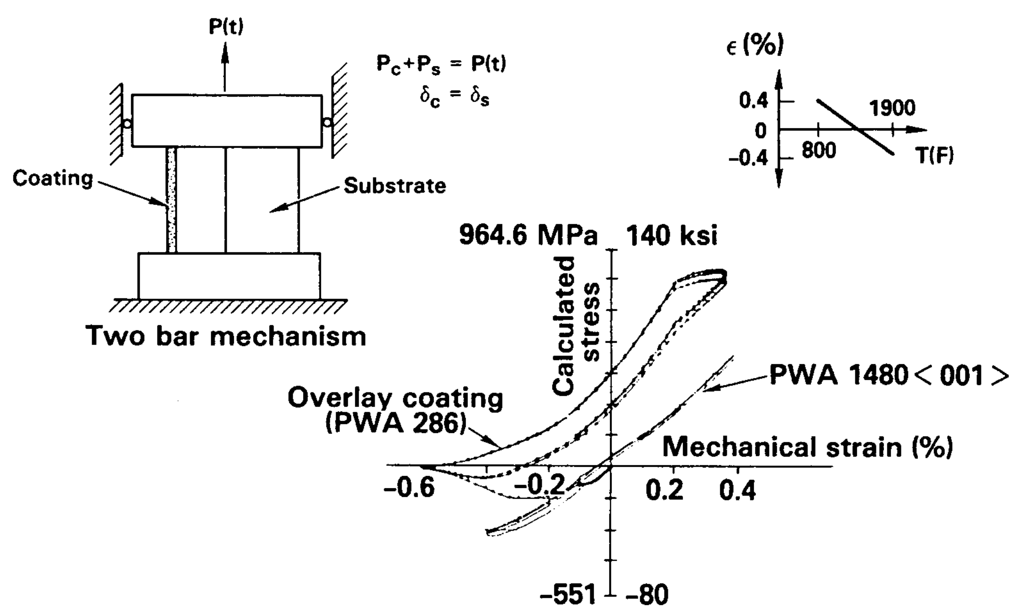
N_{si} = Cycles to initiate substrate crack.

N_{sp} = Cycles to propagate substrate crack to failure.

N_f = Total cycles to failure.

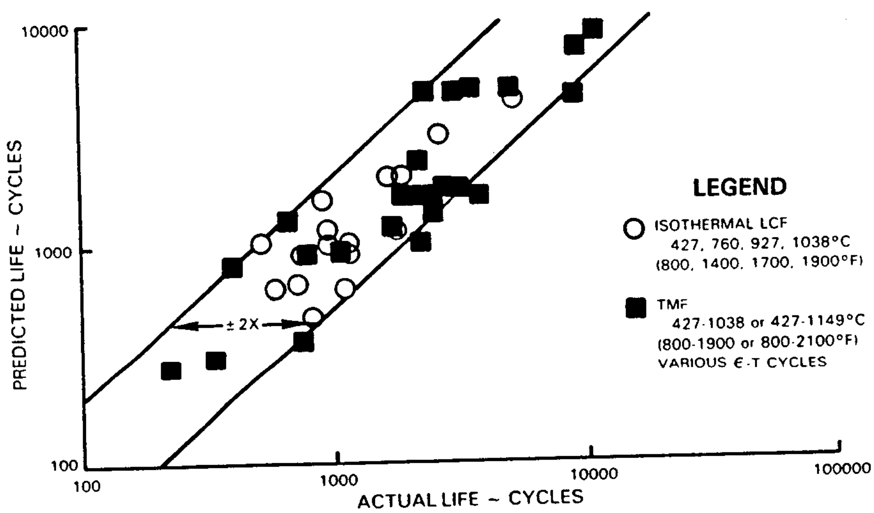
SIMPLE STRUCTURAL MODEL FOR PREDICTING COATING/SUBSTRATE BEHAVIOR

Since coating stress/strain behavior can not be measured during specimen tests, an analysis is used to obtain the non-linear coating response for life prediction. To facilitate this effort, a one-dimensional two-bar mechanism analysis is employed. As an example, the predicted response of overlay coated PWA 1480 <001> during an out-of-phase thermomechanical test is shown in the figure. The overlay coating response is highly non-linear relative to the single crystal PWA 1480 which remains nearly elastic. The coating mechanical strain range is higher than the PWA 1480 due to differences in the coefficient of thermal expansion between the two materials which is included in the two-bar model.



OVERLAY COATING CONSTITUTIVE MODEL PREDICTION OF TMF BEHAVIOR

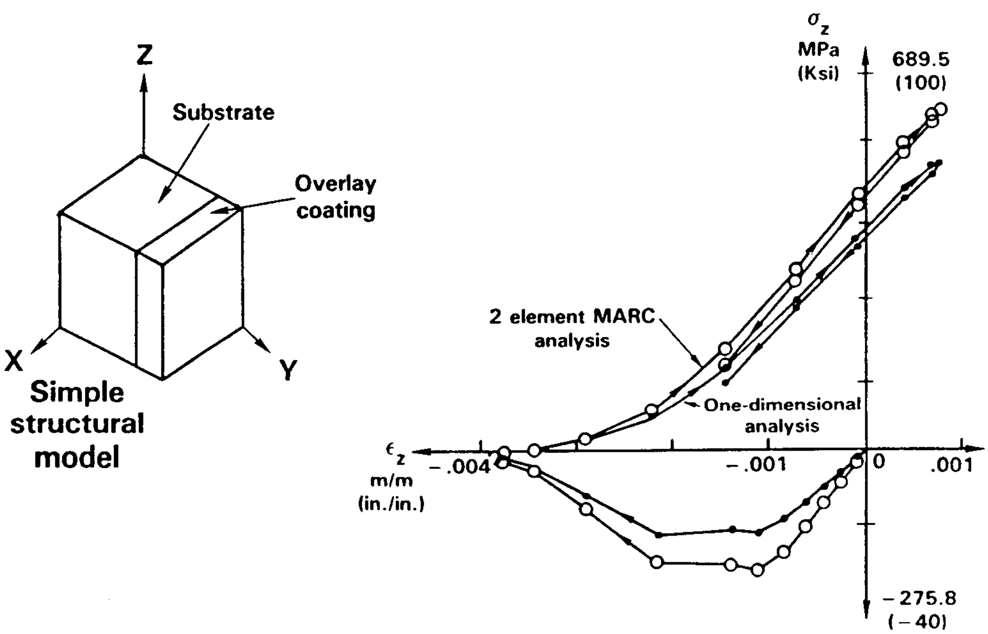
Walker's isotropic formulation (Walker, 1981) was chosen as the overlay coating constitutive model based on its ability to reproduce isothermal and thermomechanical hysteresis loop data. Shown in the figure is a comparison of the model prediction to an out-of-phase thermomechanical test cycle. The model captures the overall shape of the hysteresis loop, but overpredicts the maximum and minimum stresses. It is felt that the model predicts the coating behavior to the extcnt that current state-of-the-art viscoplastic models are capable. Baseline tests from which all model constants were determined consisted of cyclic stress relaxation tests which covered a temperature range from 427C to 1093C (800F to 2000F) (Swanson et al., 1987). MARC finite element user subroutine 'HYPELA' has been developed for the overlay coating to permit non-linear analysis of coated specimens and components.



- **Overlay coating response calculated from 2-bar analysis**

UNIAXIAL TMF INTRODUCES SIGNIFICANT BIAXIAL COATING LOADS

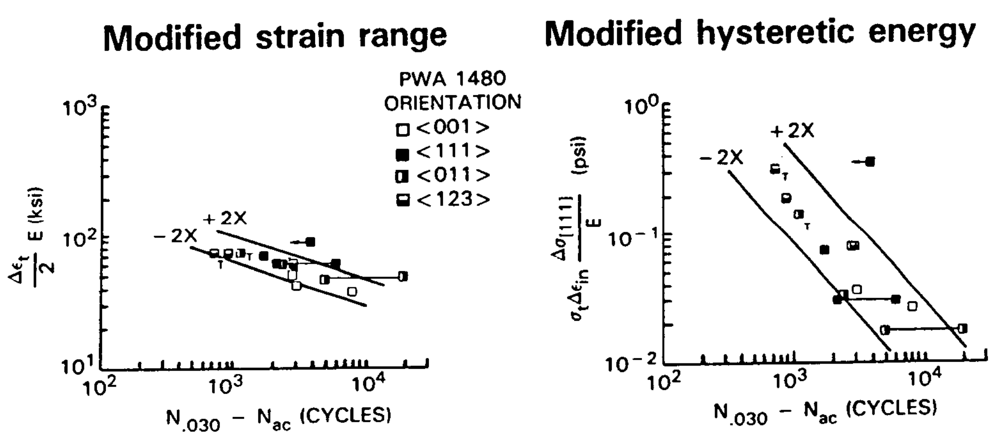
Ultimately, coated TMF life prediction must consider the biaxial coating loads introduced by the thermal growth mismatch between the coating and substrate. For example, MARC finite element analysis of a simple two element structure was performed to obtain the coating hysteretic response to a fully-reversed, uniaxial, out-of-phase TMF test conducted at 427-1038C (800-1900F), 1 cpm, and .3% mechanical strain range. Predicted hysteresis loops from the finite element and one-dimensional analyses are presented in the figure. The coating tensile hysteretic energy was obtained from the finite element analysis by the method proposed by Garud (1981). For this test condition, biaxial coating loads increased the tensile energy 70% which reduced the predicted life by a factor of about 1.5. Before the overlay coating life model is completed, all TMF test cycles must be analyzed in this manner.



PRELIMINARY PWA 1480 LIFE MODEL CORRELATIONS

Initial single crystal life correlations have been completed. The two models chosen for futher development are: an elastic modulus modified strain range and the modified hysteretic energy approach developed by DeLuca and Cowles (1985). The strain range model is attractive because mechanical strains are readily available to the turbine airfoil designer. However, it does not currently have the capability to determine cyclic strain or strain-temperature history effects. For example, two tensile strain dwell cycles, which are denoted in the figure by the subscript "T", were incorrectly correlated to have identical life with that of a non-dwell cycle. This is a serious limitation since TMF lives are highly strain-temperature history dependent (Swanson et al., 1987). On the other hand, the modified hysteretic energy model includes parameters which enable correction for strain or strain-temperature effects. This model correctly correlated the two dwell cycles from the non-dwell cycle. Unfortunately, hysteretic energy models inherantly use inelastic strain as one of their correlating parameters and, as noted previously, the single crystal TMF loops are virually elastic in nature. Therefore, although both models have advantageous aspects, they require additional refinements for TMF life prediction.

Aluminide coated specimens at 927°C (1700°F)



$$N_{.030} - N_{ac} \approx N_{sc} \text{ or } N_{si}$$

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