N88-11175

LIFE PREDICTION AND CONSTITUTIVE MODELS FOR ENGINE HOT SECTION ANISOTROPIC MATERIALS PROGRAM*

G. A. Swanson
United Technologies Corporation
Pratt & Whitney

INTRODUCTION

The purpose of this five-year program is to develop life prediction models for coated anisotropic materials used in gas temperature airfoils. In the base program, now underway, two single crystal alloys and two coatings are being tested. These include PWA 1480; Alloy 185; overlay coating, PWA 286; and aluminide coating, PWA 273. Constitutive models are also being developed for these materials to predict the plastic and creep strain histories of the materials in the lab tests and for actual design conditions. This nonlinear material behavior is particularly important for high temperature gas turbine applications and is basic to any life prediction system. This report will highlight some of the accomplishments of the program this year.

SINGLE CRYSTAL CONSTITUTIVE MODEL

A literature survey was conducted to identify constitutive models and modeling approaches that are applicable to single crystal materials. Two distinct approaches were identified. The first attempts to model the anisotropic behavior by using micromechanical processes which occur during deformation as a basis for the mathematical formulation. The second approach ignores the micromechanical processes and attempts to describe the bulk behavior through macroscopic quantities which are functions of material orientation. While some of the earlier macroscopic models can be considered "fully developed", no complete micromechanical model can be considered fully developed.

Three candidate models have been identified for further evaluation. Two of these models use the macroscopic continuum approaches. These are the classical Hill model (ref. 1) and a unified viscoplastic formulation by Lee and Zaverl, et al (ref. 2). The third model uses a micromechanical approach which is currently being developed by Dr. Kevin Walker. This model is showing the most promise and, therefore, is discussed in detail in this report.

The micromechanical model is based on slip system stresses and strains and is imbedded in Walker's unified viscoplastic formulation (ref. 3). The viscoplastic constitutive formulation based on crystallographic slip theory can be written in the form:

$$\dot{\gamma}_r = K_r^{-p} (\tau_r - \omega_r) \left|\tau_r - \omega_r\right|^{p-1}$$

*Work done under NASA Contract NAS3-23939.

where $\dot{\gamma}_r$ is the shear strain rate resolved on a particular slip system; τ, τ_r is the shear stress resolved on that system; and ω_r and K_r are evolving constants analogous to the back stress and drag stress. The term K_r accounts for the activation of slip systems other than the specific resolved one, that contribute to the shear strain.

A preliminary evaluation of this model has been made using the 982°C (1800°F) data obtained from PWA 1480. Predicted behavior differs depending on whether the model assumes activity on octahedral slip systems or on cubic slip systems, as shown in figure 1(A) through 1(C). Figure 1(A) shows the experimental cyclic hysteresis loops at 982°C (1800°F) for the <001>, <110>, and <111> orientations. For assumed octahedral slip, figure 1(B), the variation of peak stress response with direction is reasonable, but the theoretical hysteresis loop in the [001] direction is "fatter", i.e., displays a more inelastic response, than the corresponding experimental loop. At this strain range, viz. $\pm$ 0.3 percent, the experimental [001] loop is almost behaving elastically. At higher strain ranges, the response exhibits an inelastic behavior and the loop becomes "fatter".

Figure 1(C) shows the corresponding predicted loops at a 10^{-3} per second strain rate in the [001], [011] and [111] directions using the cube slip formula. The same constants were used here for the cube slip response as were used for the octahedral response, simply to see the variation of cube slip constitutive response with direction. The material constants are clearly inappropriate but suffice to show that no inelastic response is predicted in the [001] direction. Even for large strain ranges, no inelastic response is predicted in the [001] direction due to the fact that the resolved shear stress τ_{mr} is zero in each of the six slip directions when the bar specimen is pulled in the [001] direction. Clearly a mixture of octahedral and cube slip will improve the correlation between the theoretical model and the experimental results.

COATING CONSTITUTIVE MODEL

Knowledge of coating constitutive behavior is essential to the life prediction of coated materials for a number of reasons. Coatings, as will be shown below, are very often the sites of crack initiation and, therefore, the time for a crack to initiate and progress into the substrate is very important in the overall life of the component. Secondly, the coating is effectively a structural component and its stress-strain history will affect the stress-strain history of the substrate-coating interface.

The survey of candidate constitutive models for this program was limited to isotropic formulations. Data to measure any anisotropy inherent in the actual application would be well beyond the scope of this program. Models selected for evaluation have included a classical model (ref. 4), Walker's viscoplastic formulation (ref. 3), Stowell's model (ref. 5), and Moreno's simplified version (ref. 6).

Experimental data on the aluminide coating is not yet available. The testing procedures are complex and are in the development stage. For the overlay coating some cyclic-creep relaxation data have been obtained, using both hot isostatically pressed and plasma sprayed specimens, to partially evaluate the models. Comparison of cyclic-creep relaxation data against the classical model and the Walker model is shown in figure 2. In this test the classical model matches the data almost as well as Walker's model. For longer tests and/or more complex cycles, the Walker model's better accuracy may become very important.

LIFE PREDICTION MODEL

The selection process for life prediction models has not yet been focused to the extent of that for the constitutive models. However, an extensive list of candidates has been developed, and they generally fall into three broad classifications: 1) phenomenological models, 2) cumulative damage models, and 3) crack growth models.

In general, all of the phenomenological models have the advantage of simplicity and a rather direct relationship to data bases. A drawback, however, is that they are not very amenable to accounting for significant interaction effects when different damage mechanisms (cyclic creep, fatigue) operate either simultaneously or sequentially as a result of complex high temperature loading patterns. The cumulative damage (ref. 7-8) approaches assume that the plastic and creep components of inelastic strain cause damage which can be explicitly predicted and which define the state of the material. Damage is considered to be zero in the initial undamaged state and failure occurs when a critical level or limit is reached due to plastic, cyclic creep or monotonic creep deformations. A number of different definitions of damage and approaches for counting damage are used. Nearly all of these require use of a constitutive model to determine the portion of damage caused by a particular load condition. Life prediction models which use this approach are: Linear Time and Cycle Fraction, Ductility Exhaustion, Continuous Damage, Strain Range Partitioning, and Cyclic Damage Accumulation.

The model development will follow closely the results of low cycle fatigue and thermal mechanical fatigue tests.

LIFE PREDICTION TESTS

From the initial test results, the importance of the coating in influencing the substrate life is demonstrated both by the metallography of the failures and the number of cycles to failure. Comparing the fracture surface photographs in figures 3 and 4, note that the diffusion coated specimens cracked almost uniformly around the circumference, whereas the overlay coated specimens developed families of thumbnail cracks around the circumference. Also, note in figure 5 that the diffusion coated specimen is more sensitive to strain range than the overlay coated specimens.

Replica data taken during thermal mechanical fatigue tests, shown in figure 6, demonstrate that cracks in the diffusion coating grow relatively quickly around the circumference and uniformly into the single crystal, while cracks in the overlay coating penetrate the coating quickly but stop at the coating-substrate interface for an "incubation" period before proceeding into the substrate. A life prediction model must account for these differences in crack initiation behavior between coatings.

Since airfoils pass through complex thermal mechanical cycles,, the life prediction model must address the variation in temperature and strain through each cycle. Various thermal mechanical fatigue cycles are being tested. One interesting result is shown in figure 7. Two cycles were run with the same end points and, despite the differences in cycle shape, the lives were nearly the same. Other cycle shapes are likely to give significantly different lives.

To better understand the behavior of the coating on the substrate in a thermal mechanical fatigue cycle, a two element model was developed with one element representing the overlay coating and the other the substrate. This simple structure, utilizing the Walker constitutive model for the coating, and a simple constitutive model for the substrate, was analytically run through three cycles. As shown in figure 8, the coating mechanical strain-stress history is considerably different from that of the substrate. In each cycle the coating stress relaxes to zero stress at maximum temperature conditions due to the coating's high creep rate at these conditions. The resulting hysteresis loop should provide important parameter data for a coating cracking model.

FUTURE WORK

In the coming year, additional cyclic tests are planned to: 1) develop the constitutive model, 2) assist in the life prediction model formulation, and 3) evaluate constants for the models. Also, assuming Option 1 of the program is exercised, model life development will be extended to airfoil root attachment temperatures, stress levels, and notch stress concentrations.

REFERENCES

1. Hill, R.: "A Theory of the Yielding and Plastic Flow of Anisotropic Metals," Proc. Royal Society of London, Ser. A, Vol. 193, pp. 281-297, 1948.

2. Lee, D.; Zaverl, F., Jr.; Shih, C. F.; and German, M. D.: "Plasticity Theories and Structural Analysis of Anisotropic Metals," Report No. 77CRD285, General Electric Corporate Research and Development Center, Schenectady, New York, 1977.

3. Walker, K. P.: "Research and Development Program for Nonlinear Structural Modeling With Advanced Time-Temperature Dependence Constitutive Relationships," NASA CR-165533, November, 1981.

4. Kraus, H.: Creep Analysis, John Wiley & Sons, Inc., New York, Chapter 2, 1980.

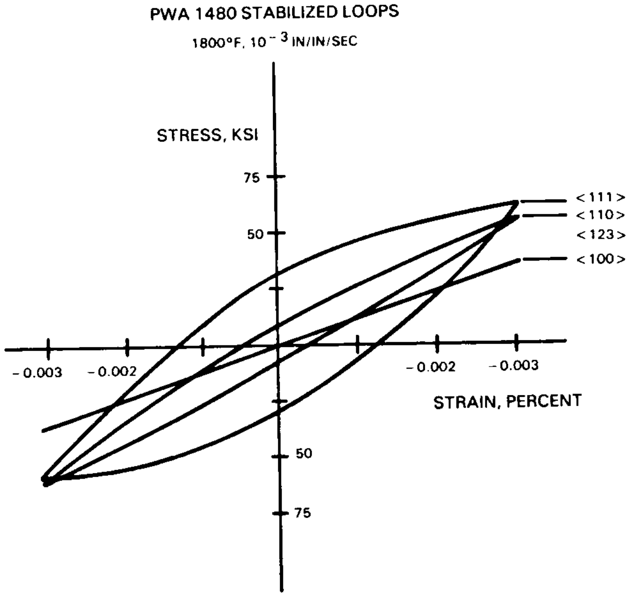
5. Stowell, E. Z., et al: "Predicted Behavior of Rapidly Heated Metal in Compression," NASA TR R-59, 1960.

6. Moreno, V.: "Development of a Simplified Analytical Method for Representing Material Cyclic Response," NASA CR-168100, January, 1983.

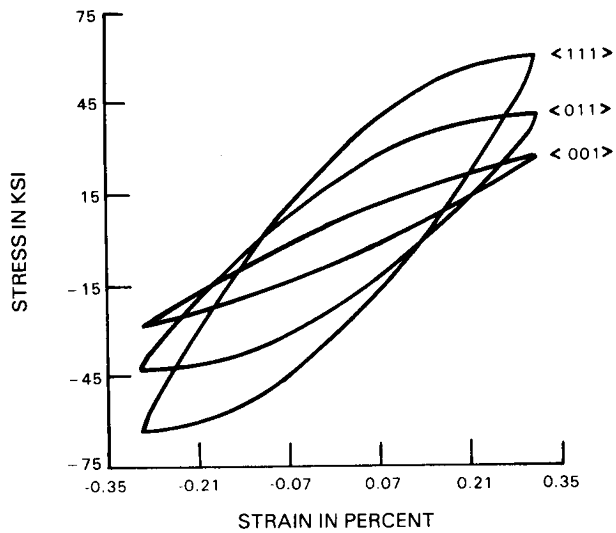
7. Lemaitre, J.; and Chaboche, J. L.: "A Non-Linear Model for Creep Fatigue Damage Cumulation and Interaction," Mechanics of Viscoplastic Media and Bodies, J. Hult, Ed., Springer-Verlag, pp. 291-301, 1975.

8. Lemaitre, J.; and Plumtree, A.: "Application of Damage Concepts to Predict Creep Fatigue Failures," J. Eng. Materials and Technology, Vol. 10, ASME, pp. 284-292.

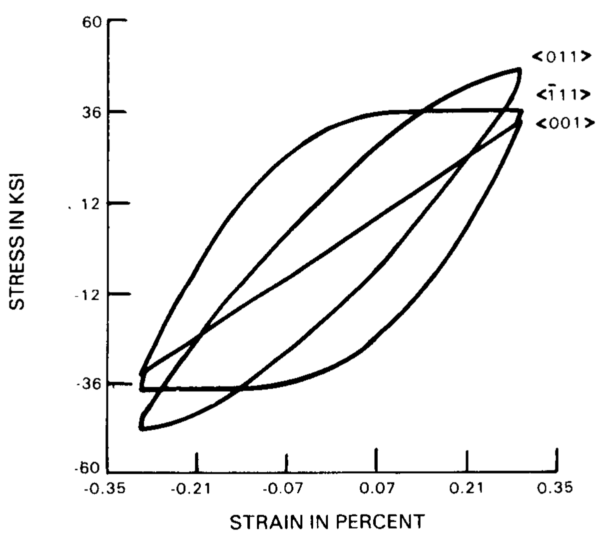
9. Swanson, G. A.; and Bill, R. C.: "Life Prediction and Constitutive Models for Engine Hot Section Anisotropic Materials," AIAA-85-1421, AIAA/SAE/ASME 21st Joint Propulsion Conference, Monterey, California, 1985.



(A) Experimental Hysteresis Loops for PWA 1480 at 982°C (1800°F) at 10^{-3} Sec^{-1} Strain Rate



(B) Octahedral Slip Predictions of Hysteresis Loops for PWA 1480 at 982°C (1800°F)

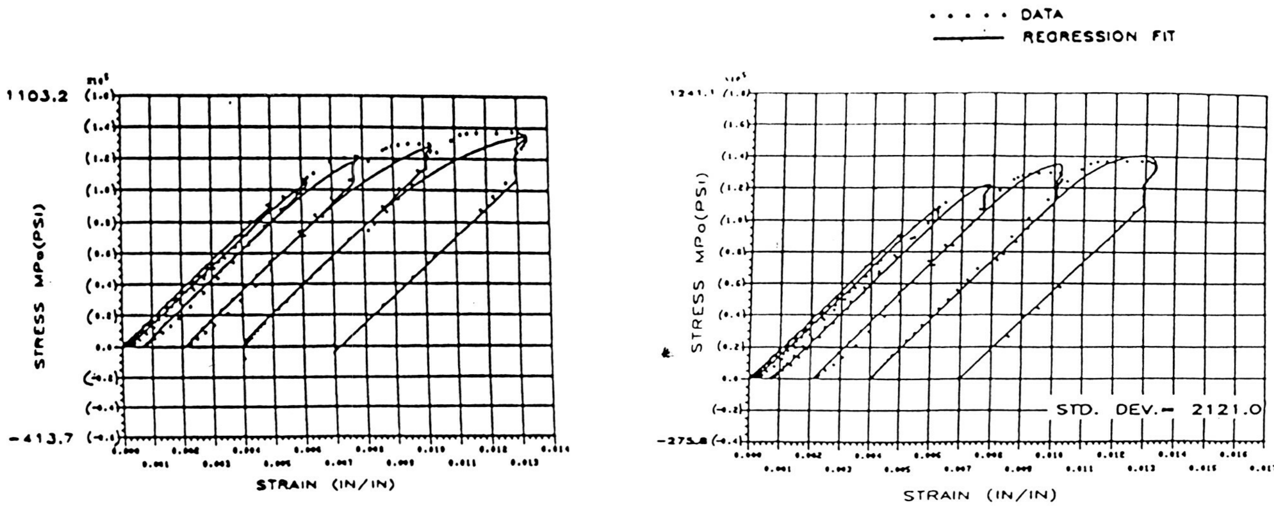


(C) Cube Slip Predictions of Hysteresis Loops for PWA 1480 at 982°C (1800°F)

Figure 1

COATING CONSTITUTIVE MODEL-DATA COMPARISON

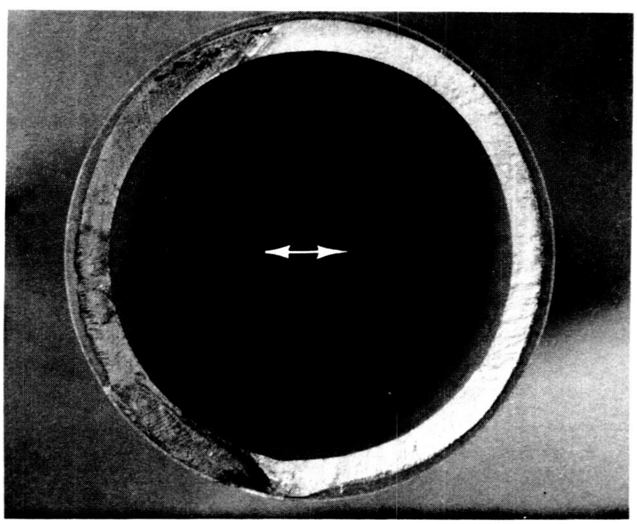
CYCLIC - CREEP RELAXATION TEST AT 538°C (1000°F)



CLASSICAL MODEL

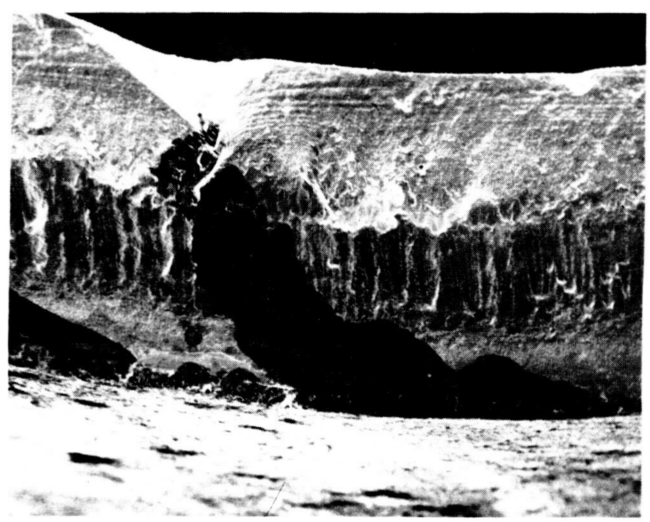
WALKER MODEL

Figure 2



6X

(A) Circumferential Cracking



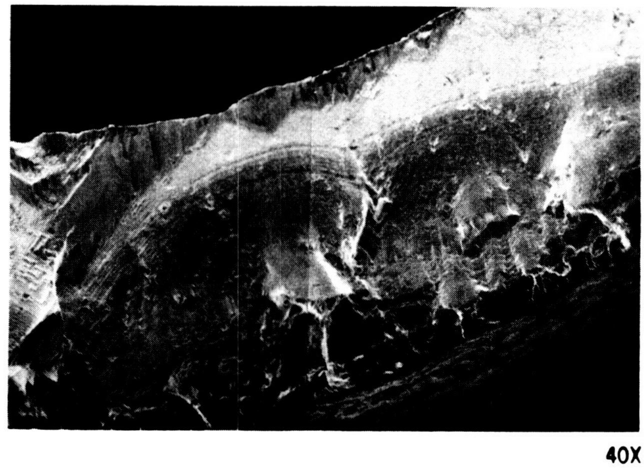
50X

(B) Faint Fatigue Striations

Figure 3 PWA 273 Coated PWA 1480 <100>; Specimen JB-22; After Being Thermal Mechanical Fatigue Tested at 427-1038°C (800-1900°F) $\Delta\epsilon = \pm 0.275\%$, 1 CPM, Out-of-Phase for 3772 Cycles

ORIGINAL PAGE IS
OF POOR QUALITY

(A) Multiple Small Thumbnail-Like Fatigue Cracks



(B) Faint Fatigue Striations

Figure 4 PWA 286 Coated PWA 1480 <100>; Specimen JB-9; After Being Thermal Mechanical Fatigue Tested at 427-1038°C (800-1900°F) $\Delta\epsilon = \pm 0.4\%$, 1 CPM, Out-of-Phase for 1878 Cycles

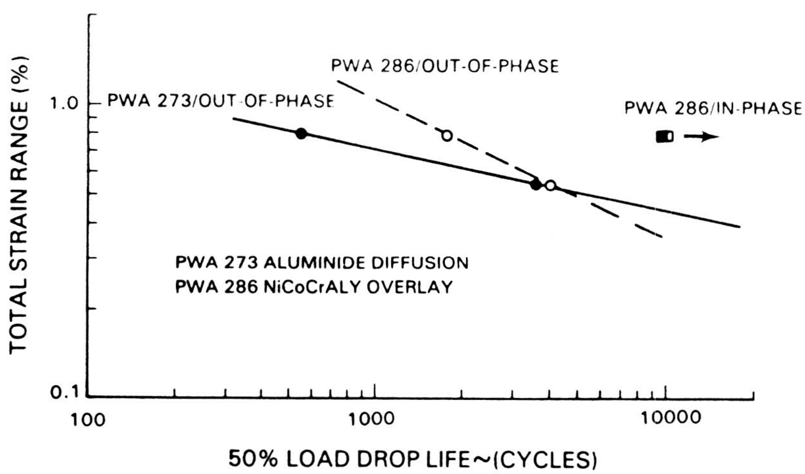


Figure 5 Thermal Mechanical Fatigue Life Vs. Strain Range for Coated PWA 1480 427-1038°C (800-1900°F)

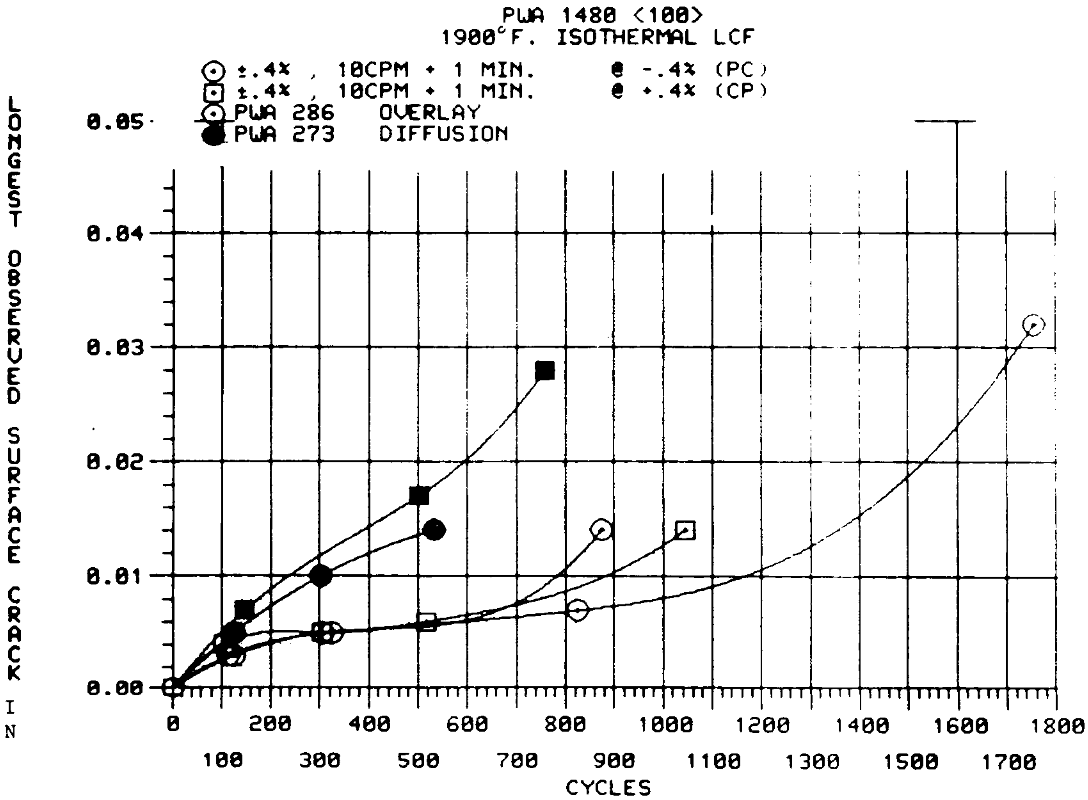
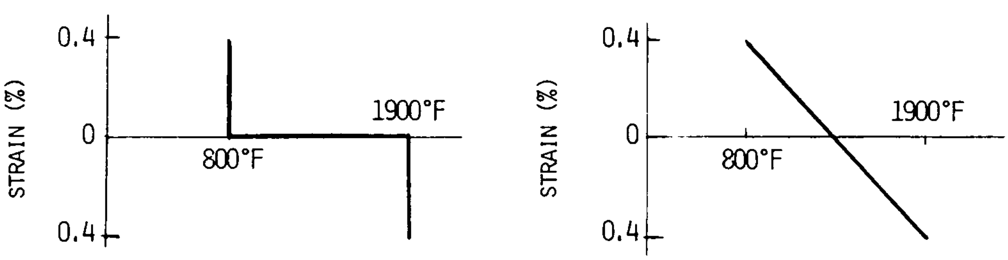


Figure 6 Comparison of Crack Growth with Diffussion and Overlay Coatings



COATING	LIFE	LIFE
ALUMINIDE, PWA 273	876 CYCLES	580 CYCLES
OVERLAY, PWA 286	1847	1878

Figure 7 Coated PWA 1480 Life Comparison: Two TMF Cycle Shapes

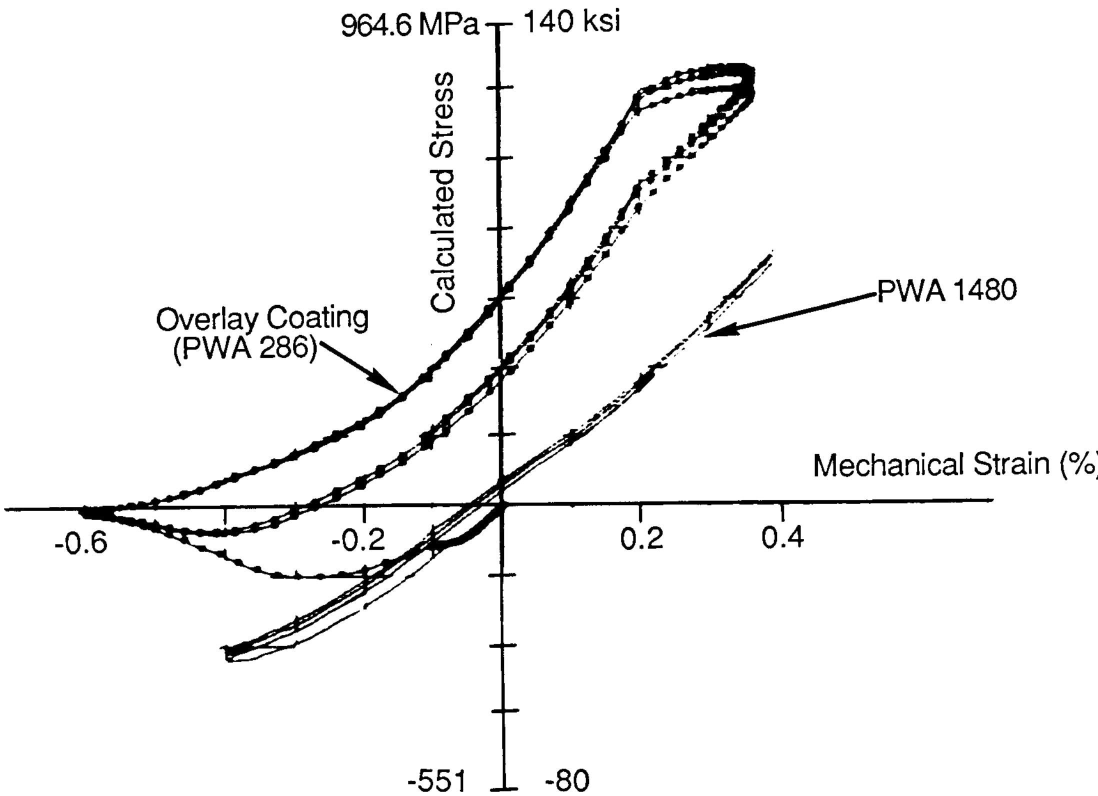


Figure 8 TMF Cycle - Coating and Substrate Stress-Strain History
Out of Phase Cycle
Temperature Range 427°C - 1038°C (800°F - 1900°F)
Strain Range ± 0.4 Percent