P10 Thermomechanical Fatigue Life Prediction Model for Advanced Gas Turbine Materials[1]

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Abstract

The main objective of the ATS research program is directed towards life prediction modeling of coated advanced gas turbine materials due to thermomechanical strain cycling. Emphasis is placed on life characterization on the basis of low cycle fatigue (LCF) under isothermal conditions and also on thermomechanical fatigue (TMF). In addition, the material deformation response to TMF is to be analyzed in terms of fracture mechanisms, microstructure changes, and environmental effect. IN-738LC was chosen as a basic substrate material with overlay (MCrAlY) and aluminide (NiAl) coatings.

Thermomechanical fatigue (TMF) is a unique type of fatigue in which material is simultaneously subjected to fluctuating loads and temperatures. Isothermal life prediction techniques are often not applicable to TMF conditions since mechanical properties are typically temperature dependent and because different damage mechanisms can arise. Many service conditions may be simulated using simple relationships between the thermal and mechanical strains. In-phase (IP) TMF occurs when the maximum strain and peak cycle temperature coincide whereas the maximum strain and lowest cycle temperature coincide during out-of-phase (OP) TMF. "OP TMF" cycles represent the TMF damage which occurs on the leading edge of a gas turbine blade from repeated turbine starts and stops. Turbine blades are routinely coated with either an aluminide, overlay, or thermal-barrier coating to either inhibit oxidation or hot corrosion or to reduce substrate temperature. It is imperative that the coating maintain adherence to the blade without cracking or spalling to ensure maximum substrate protection. However, properties such as Young's moduli, thermal expansions and inelastic deformation behavior of the coatings are highly dependent upon temperature and often differ from the respective substrate properties, thereby complicating TMF life prediction. Accurate TMF life estimates of coated turbine blades should account for these temperature-dependent properties of both the coating and substrate.

The project was completed with the development of a new life prediction model to account for thermomechanical strain cycling effect on fatigue for coated IN738LC. The model has two components:

[1] Research sponsored by U.S. Department of Energy's Morgantown Energy Technology Center, under cooperative agreement DE-FC21-92MC29061 with the South Carolina Energy Research and Development Center, subcontract AGTSR 930-1SR012D.

- A viscoplastic component which accounts for strain/temperature cycling response of substrate and coatings in terms of hysteresis loops. These loops characterize the evolution of stress/strain/cycle up to mid-life cycle where the mid-life cycle represents the average cyclic deformation of the material. The outcome of this approach is to predict the maximum stress and strain range at the mid-life cycle where stress and strain are saturated.

- A tensile energy approach is the second component of the life prediction model which assess the damage incurred in the material as a result of TMF. The damage process with mean stress and creep effect due to dwell-time are incorporated for cycles to failure prediction.

In addition, a TMF crack growth model has been developed which shows the acceleration and retardation of cracks due to the types of coatings applied to the substrate.

The outcome of the ATS research program is a significant contribution to life prediction methodology particularly for TMF problems since TMF cracking is the primary mode of mechanical failure for first stage blades in gas turbines. The life prediction methodology which has been developed and the microstructure failure analysis resulting from this research program are being incorporated in a "mechanics of material course" taught at Penn State University and the result of the ATS research program are being presented at engineering conferences.

The PI of the research program acknowledges the contribution of our industrial partners Westinghouse Electric, Power Generation Division in Orlando, FL, and Allied Signal Aerospace Co., Phoenix, AZ.

LIFE PREDICTION OF ADVANCED MATERIALS FOR GAS TURBINE APPLICATION

Contract # AGTSR-93-01-SR012D
Sponsored by : DOE-FETC/SCEC

SAM Y. ZAMRIK : PI
Pennsylvania State University

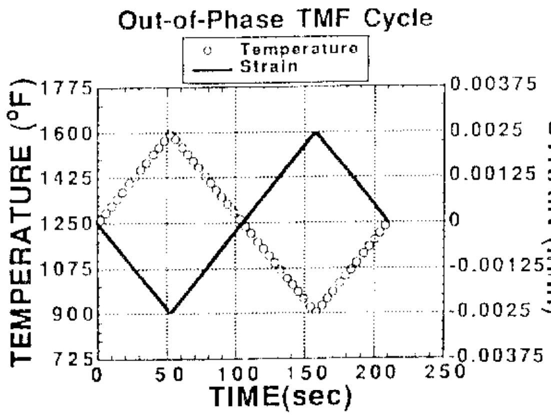
Prediction of TMF Stress-Strain Response (Hysteresis Loop) using Viscoplastic Model

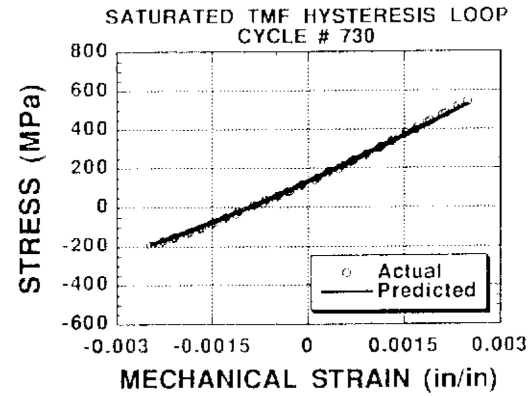
Aluminide (NiAl) Coated IN-738LC

Prediction from first cycle to mid-life cycle (saturation cycle)
$\Delta\varepsilon_{mech}$=0.8%, O.P. TMF, ΔT=900-1600°F, N_i=190

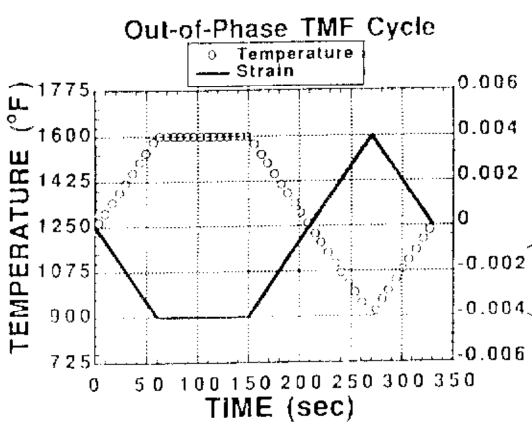
Predicted Mid-Life Out-of-Phase TMF Hysteresis Loops Overlay (NiCoCrAlHfSi) Coated IN-738LC

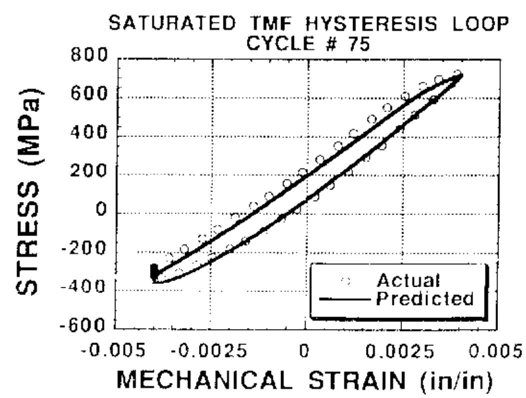
$\Delta\varepsilon_{mech}$=0.5%, O.P. TMF, ΔT=900-1600°F, N_i=2058





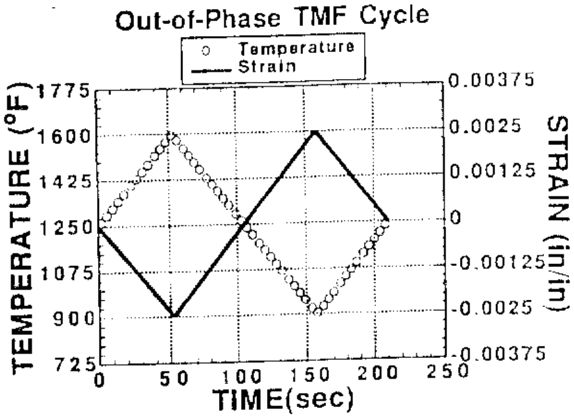
$\Delta\varepsilon_{mech}$=0.8%, O.P. TMF, ΔT=900-1600°F, t_h=90 sec(comp), N_i=189

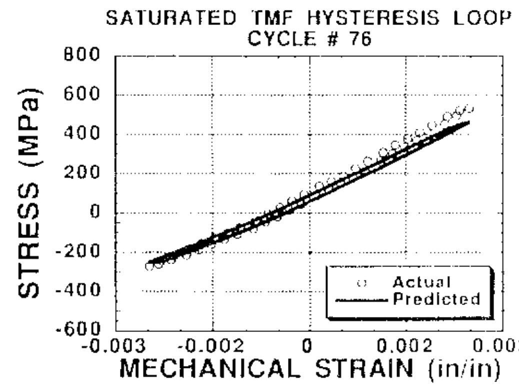




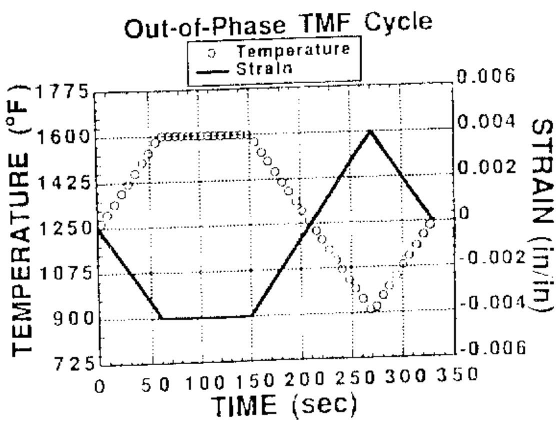
Predicted Mid-Life Out-of-Phase TMF Hysteresis Loops
Aluminide (NiAl) Coated IN-738LC

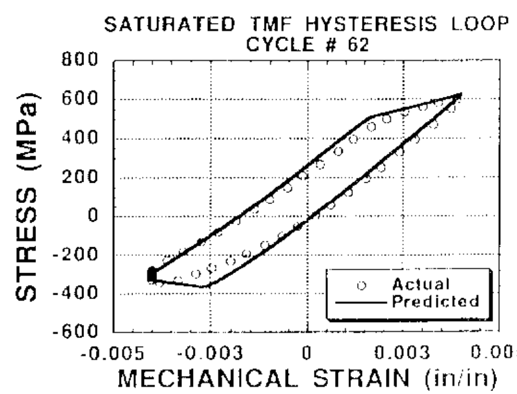
$\Delta\varepsilon_{mech}$=0.5%, O.P. TMF, ΔT=900-1600˚F, N_i=360





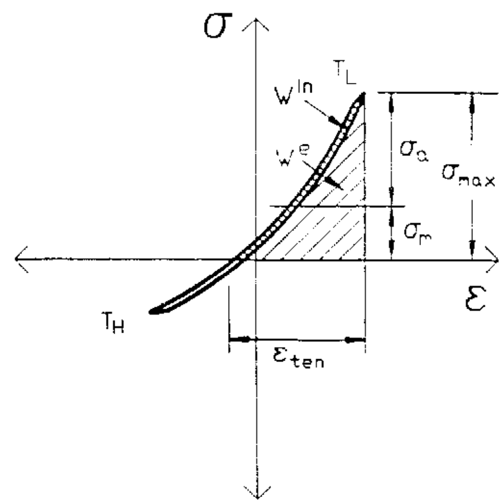
$\Delta\varepsilon_{mech}$=0.8%, O.P. TMF, ΔT=900-1600˚F, t_h=90 sec(comp), N_i=152



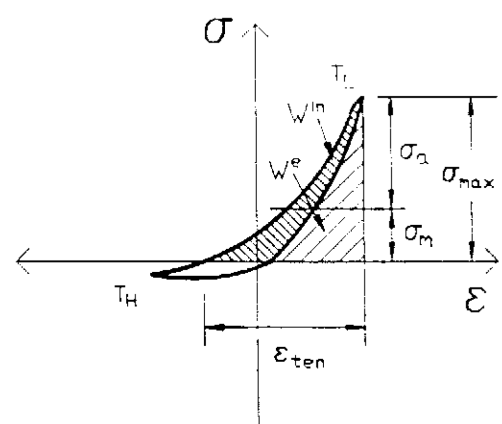


TMF NiCoCrAlY COATING MID-LIFE STRESS/STRAIN CYCLE

TYPICAL OP TMF MID-LIFE HYSTERESIS LOOP FOR IN-738LC



TYPICAL OP TMF MID-LIFE HYSTERESIS LOOP FOR OVERLAY COATINGS



Schematic illustration of tensile elastic energy, W^e and tensile inelastic energy, W^{in}, on typical IN-738LC and overlay coating OP TMF hysteresis loops.

The TMF Model

- The Life Prediction Model is Based on a Modified Energy Criterion expressed as:

$$N_f = A\ W_T^{\ B}\ f^{\ c} \text{ ---- (Ostergren)}$$

- Fatigue Life Can Be Expressed As:

$$N_f = f\ [\Delta W,\ h(t),\ r(T)\ ]$$

or :

$$N_f = A\ (\Delta W)^B\ [h(t)]^C\ r[(T)]^D$$

The Energy Approach

- The energy paramter is expressed as:

$$\Delta W = W_f / W_t$$

where:

$$W_f = \sigma_{max} \varepsilon_{ten}$$

$$W_t = \sigma_u \varepsilon_f$$

Where: - W_f is the cyclic fatigue energy at mid life hysteresis loop where the stress is tensile.

- W_t is the static energy.

Time-Temperature Functions

- The hold-time function:

$$h(t) = [1 + t_h/t_c]$$

t_h = length of compressive hold-time

t_c = length of total cycle time including hold-time

- The elevated temperature function:

$$r(T) = \exp\{- Q / R (T_{max} - T_o)$$

TMF LIFE MODEL

- The Cyclic Fatigue Life Parameters:

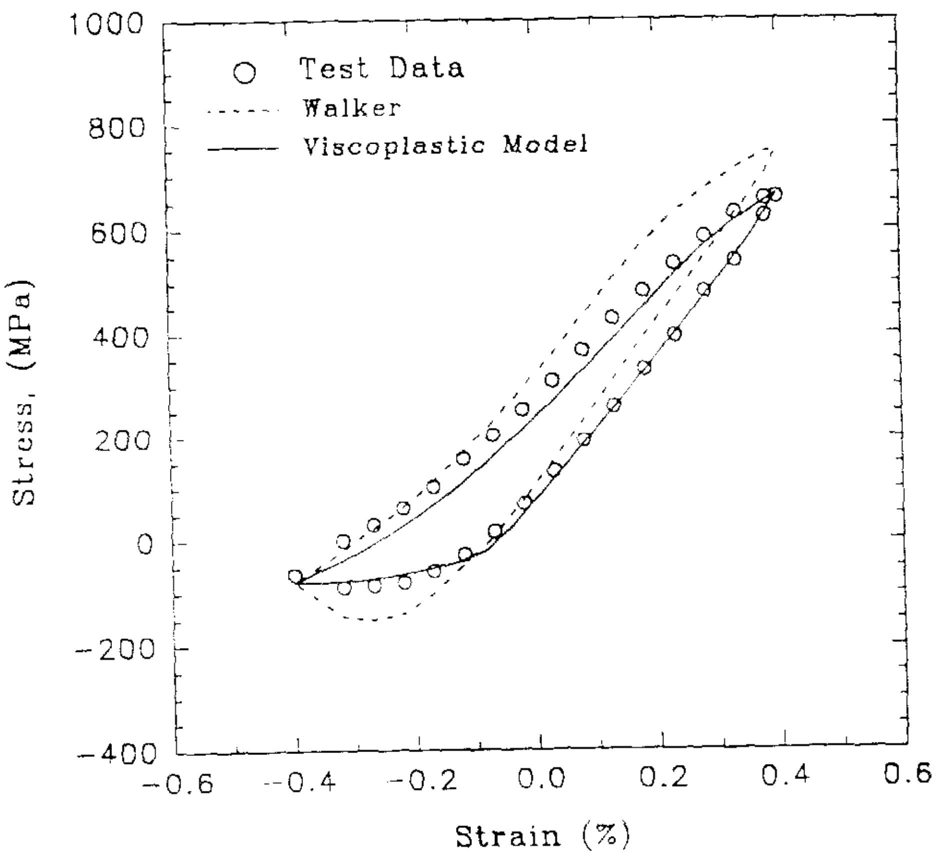
$$N_f = A\,(\Delta W)^B\,[h(t)]^C\,r[(T)]^D$$

Can Now Be Expressed in a Final Form:

$$N_f = A\{(\sigma_{max}\,\varepsilon_{ten}) / (\sigma_u\,\varepsilon_f)\}^B\,[1 + t_h/t_c\,]^c$$

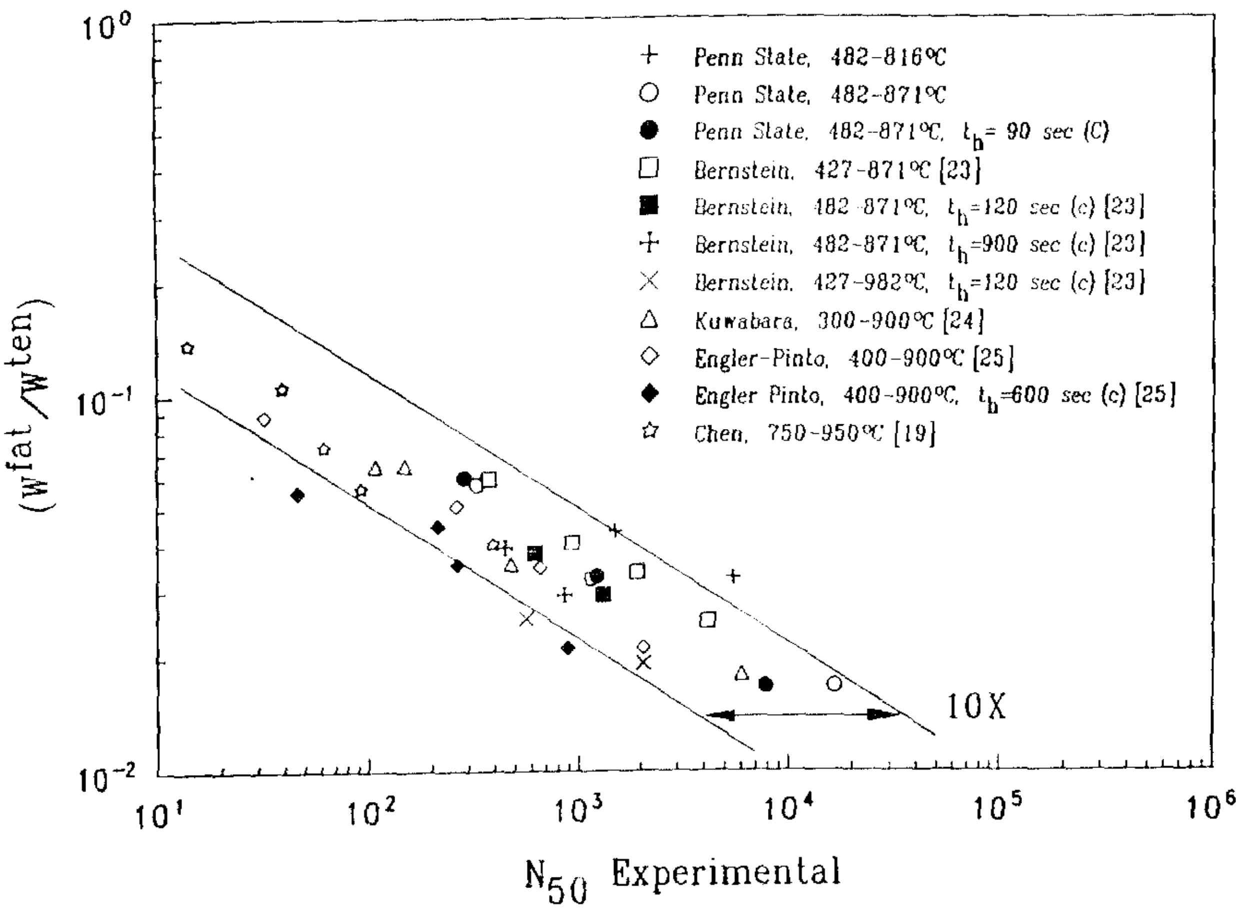
$$*\ \exp\,\{-\,Q / R\,(T_{max} - T_o)$$

MID-LIFE STRESS/STRAIN CYCLE - TENSILE ELASTIC ENERGY FOR IN738LC & OVERLAY COATING



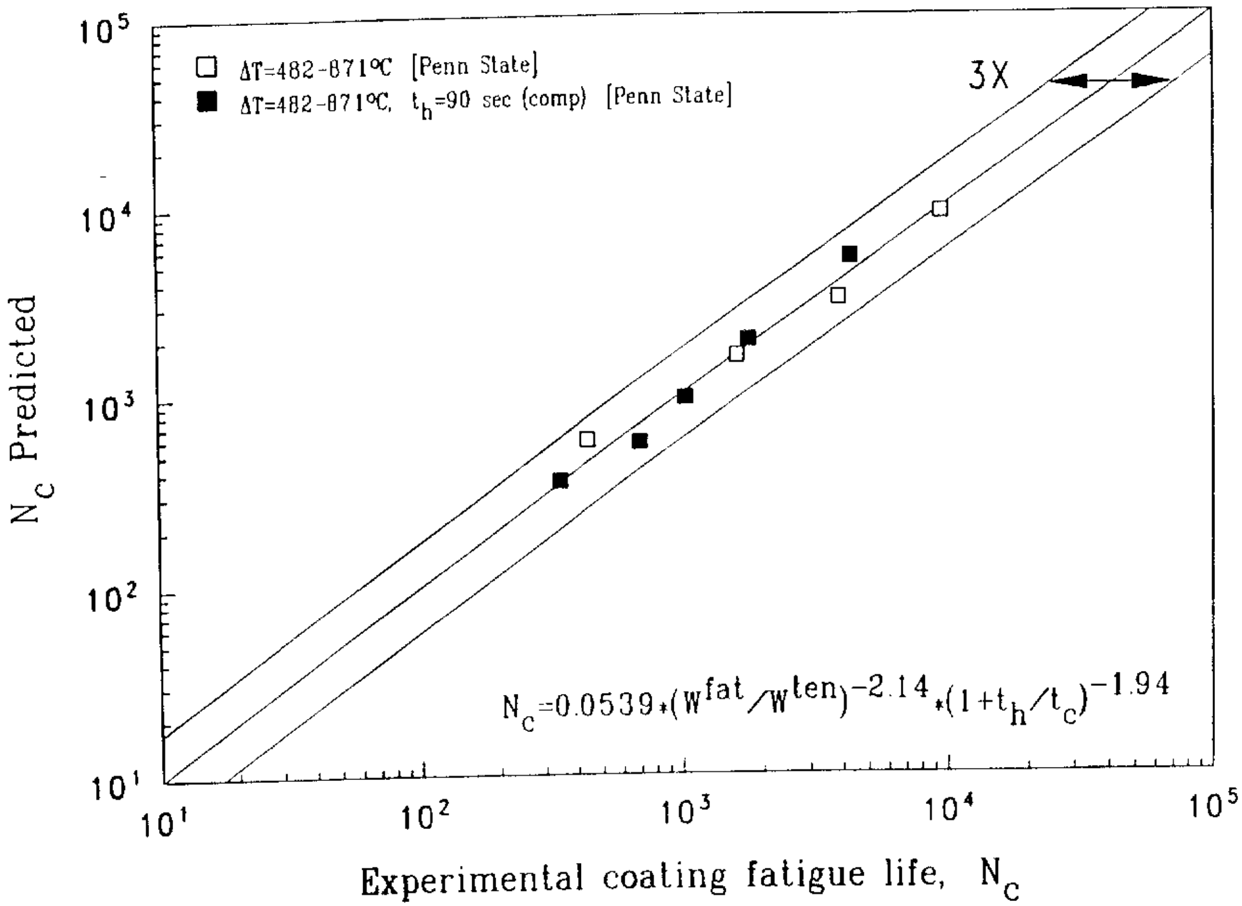
Viscoplastic model predictions for pure NiCoCrAlY overlay coating subjected to OP TMF. $\Delta\varepsilon_{mech}$=0.8%, ΔT=427-871°C.

DATA SCATTER



Correlation of uncoated IN-738LC OP TMF data using ΔW, the ratio of cyclic to static energy.

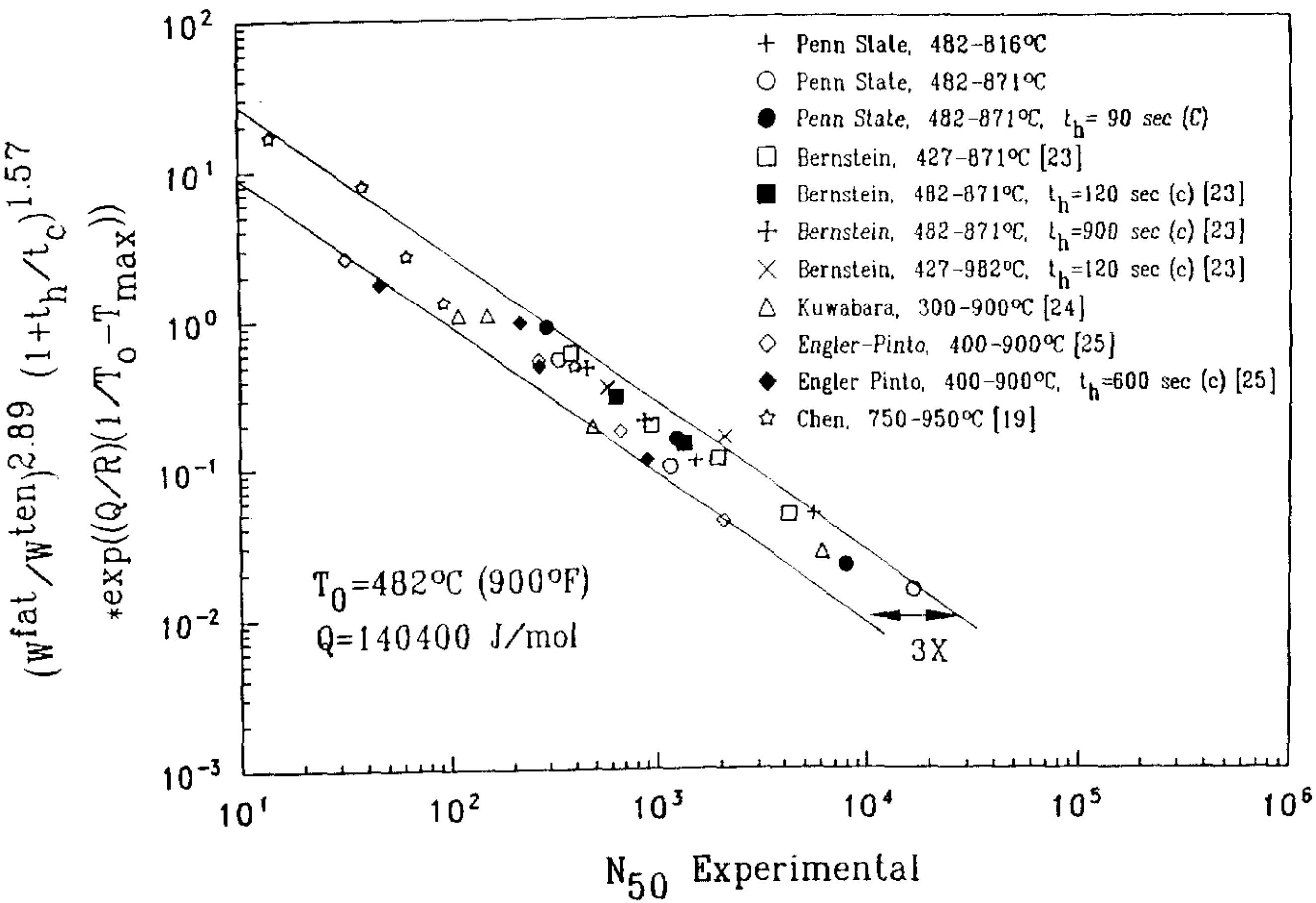
COATING FATIGUE LIFE



Life prediction results for crack initiation and propagation through a CoNiCrAlY overlay coating due to OP TMF.

DATA ANALYSIS

LIFE PREDICTION MODEL



Correlation of uncoated IN-738LC OP TMF data using proposed life prediction model consisting of three damage components: ΔW, the ratio of cyclic to static energy, h(t), the hold-time damage parameter and r(T), the elevated temperature damage component.

CRACK GROWTH MODEL FOR COATING

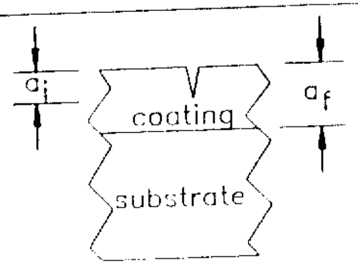
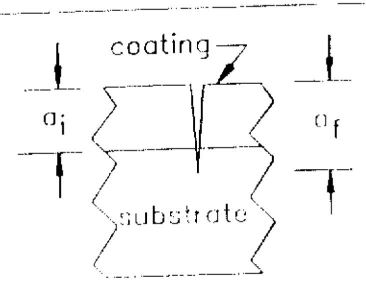
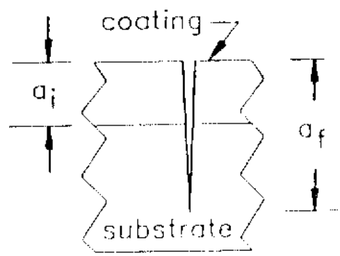
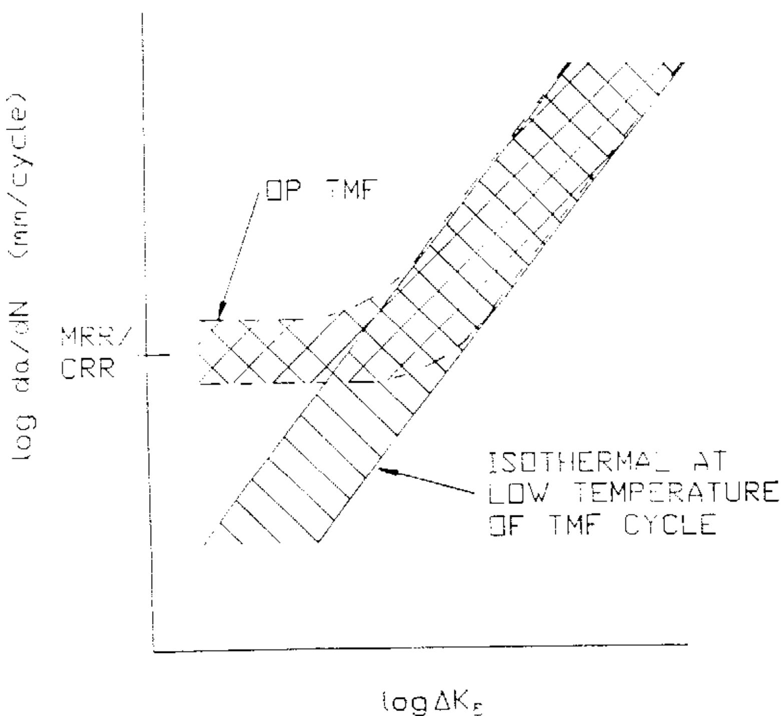
Case "s"	Case "sc"	Case "c"
Fatal specimen crack from the substrate – coating crack within coating	Fatal specimen crack from the substrate – coating crack penetrates substrate	Fatal specimen crack originates in coating
 Longitudinal X–section	 Longitudinal X–section	 Longitudinal X–section
$N_{(+)} = \int_{a_i}^{a_f} \frac{1}{A\Delta K_i^n + CRR} da$ $N_c = N_{spec} + N_{(+)}$	$N_{(-)} = \int_{a_i}^{a_f} \frac{1}{A\Delta K_i^n + MRR} da$ $N_c = N_{spec} - N_{(-)}$	$N_{(-)} = \int_{a_i}^{a_f} \frac{1}{A\Delta K_i^n + MRR} da$ $N_c = N_{spec} - N_{(-)}$

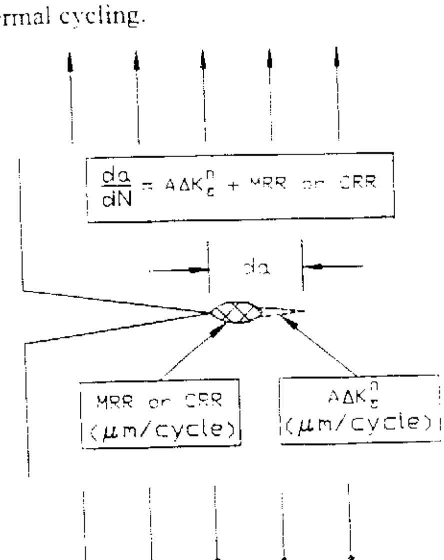
Illustration of the TMF crack growth model applied to coated IN-738LC specimens tested at Penn State to determine N_c, the number of fatigue cycles to initiate and grow a crack through the coating.

TMF CRACK GROWTH RATES

CRACK ADVANCE DUE TO OXIDATION & MECHANICAL DAMAGE



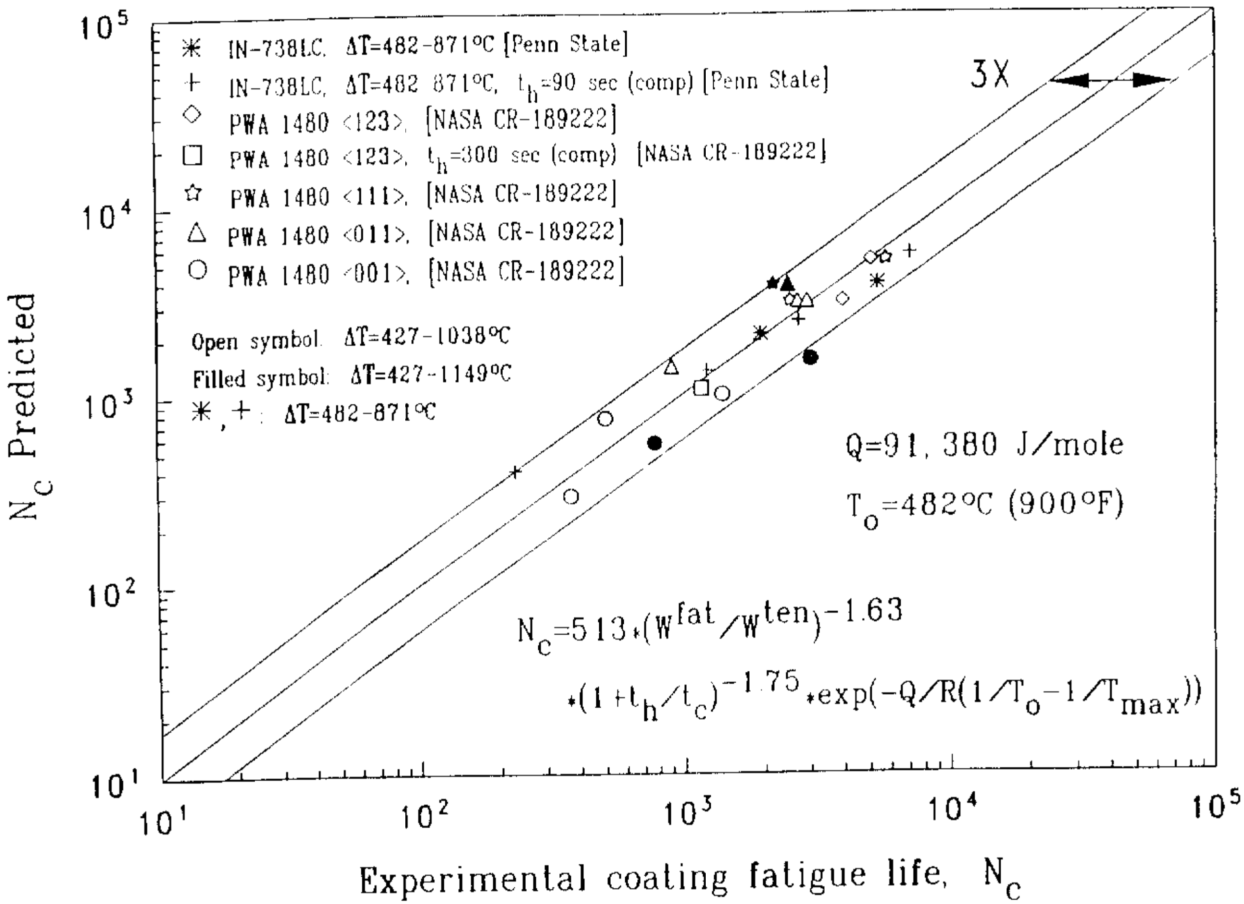
Schematic illustration of crack growth rates under OP TMF cycling and isothermal cycling.



Schematic illustration of crack advance due to a combination of oxidation and mechanical damage.

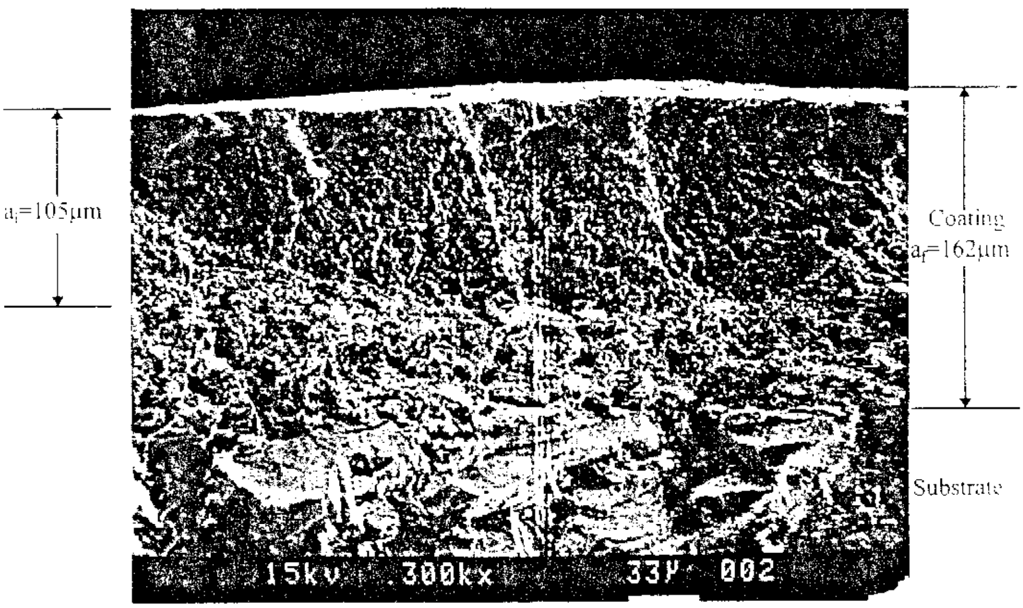
TMF LIFE PREDICTION

CRACK INITIATION & GROWTH THROUGH NiCoCrAlY COATING



Life prediction results for crack initiation and propagation through a NiCoCrAlY overlay coating due to OP TMF.

FATIGUE CRACK FRONT IN738LC+CoNiCrALY OVERLAY



Semi-elliptical fatigue crack in CoNiCrAlY overlay coating. $\Delta\varepsilon_{mech}$=0.5%, OP TMF, ΔT=482-871°C, N_{50}=1899.

where:

$$M_1 = 1.13 - 0.09\left(\frac{a}{c}\right)$$

$$M_2 = -0.54 + \frac{0.09}{0.02 + \frac{a}{c}}$$

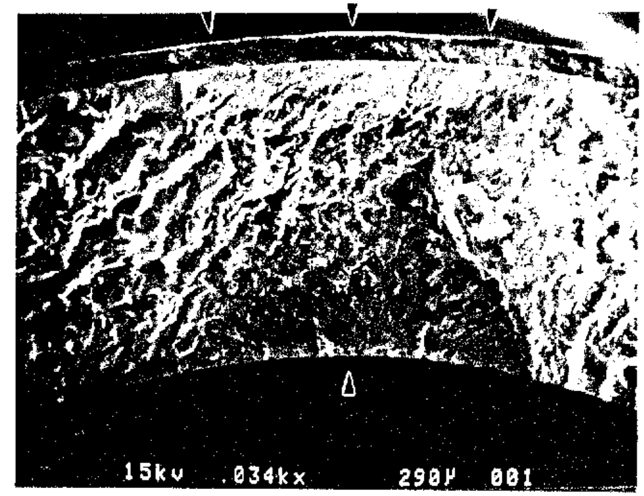
$$M_3 = 0.5 - \frac{1.0}{0.65 + \frac{a}{c}} + 14\left(1.0 - \frac{a}{c}\right)^{24}$$

Overlay (NiCoCrAlHfSi) Coated IN-738LC

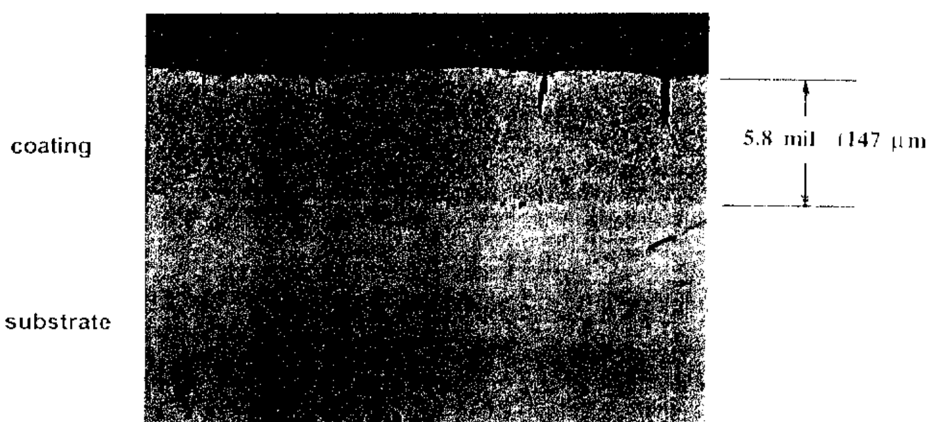
Effect of hold-time on TMF failure mode

$\Delta\varepsilon_{mech}$=0.5%, O.P. TMF, ΔT=900-1600°F, t_h=90 sec (comp), N_i=643.

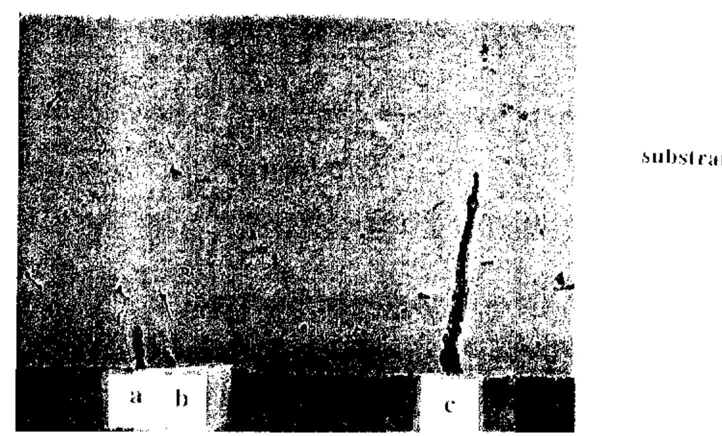
a) One "long" overlay coating surface crack.



b) Fatigue crack initiations within coating and at uncoated inner wall.



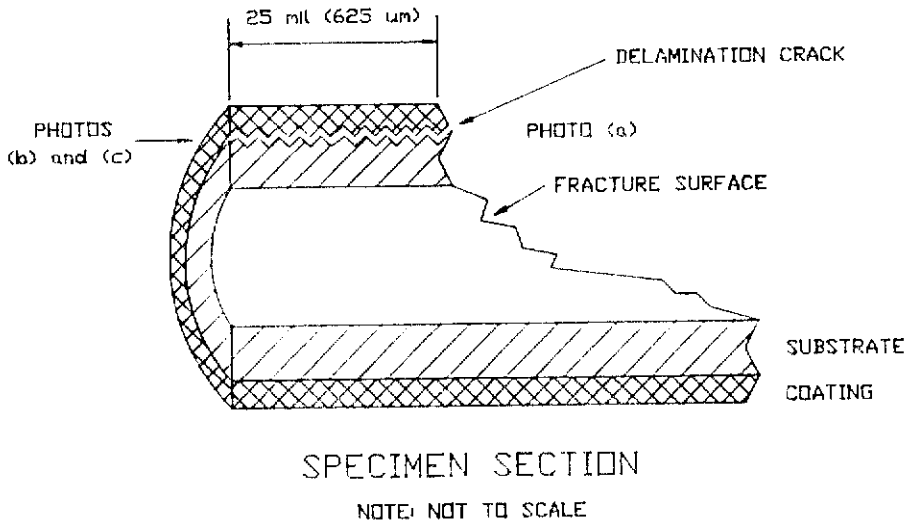
c) Fatigue crack initiation and blunting in overlay coating. Crack lengths from 0.5 mil (13 µm) to 2.3 mil (58 µm). (170X)

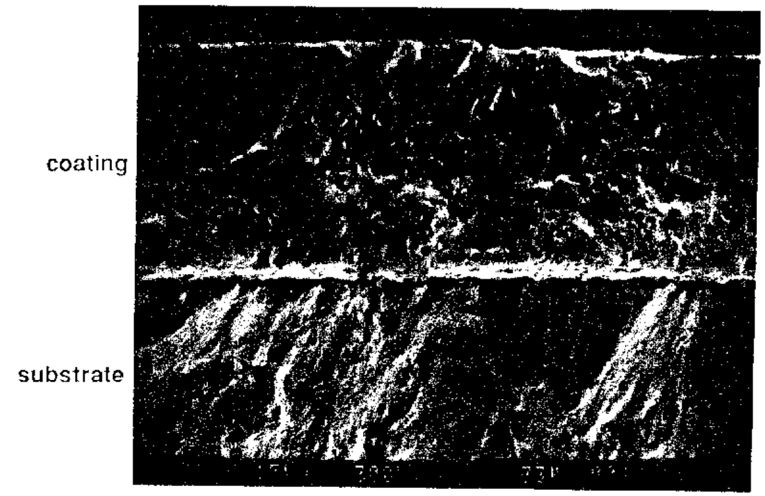


d) Crack initiation and growth from uncoated inner wall. Crack depths: a) 1.9 mil (48 µm), b) 1.0 mil (25.4 µm), c) 8.8 mil (224 µm). (170X)

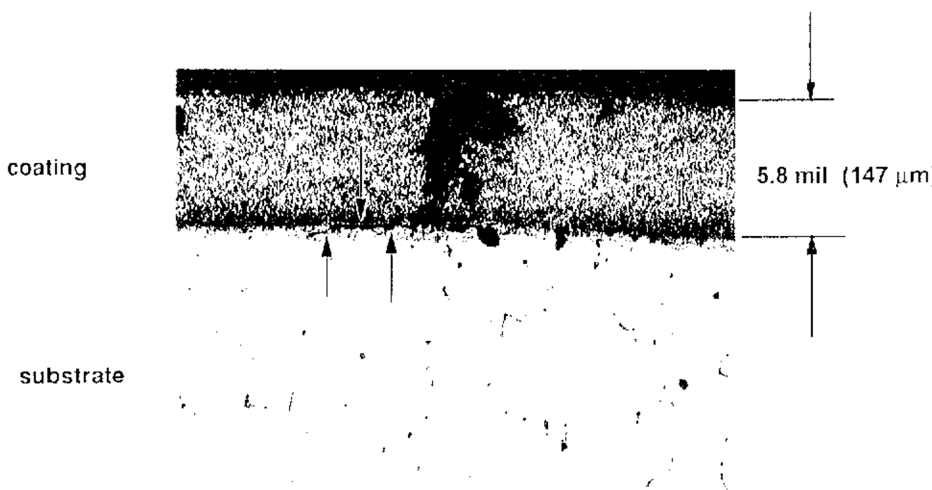
Overlay (NiCoCrAlHfSi) Coated IN-738LC

$\Delta\varepsilon_{mech}$=0.5%, O.P. TMF, ΔT=900-1600°F, N_i=2058

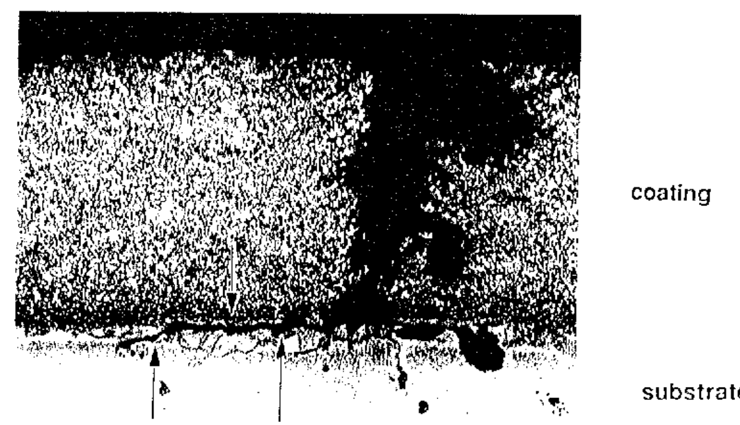




a) **Fracture surface.**



b) Delamination crack at low magnification (170X)

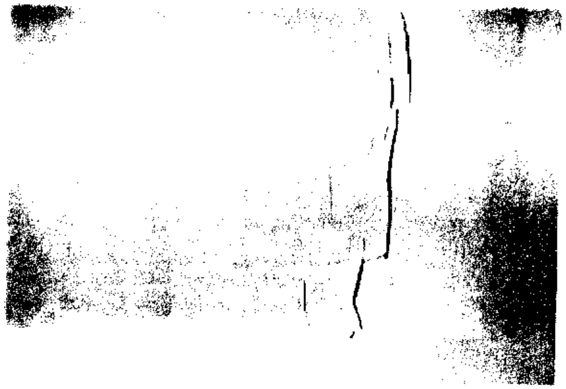


c) Delamination at the coating / substrate interface (345X)

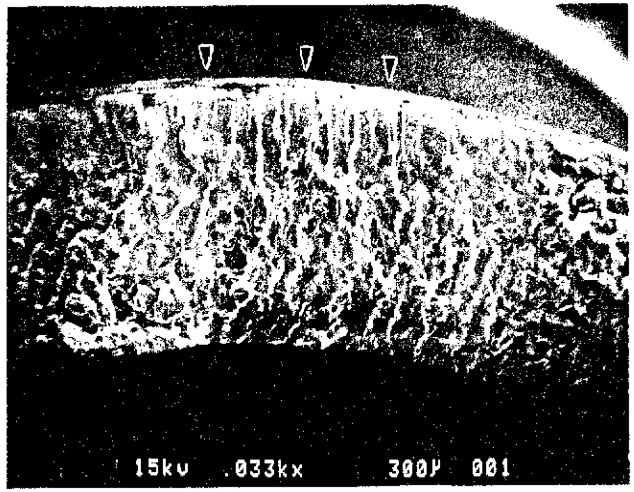
Aluminide (NiAl) Coated IN-738LC

Effect of hold-time on TMF failure mode

$\Delta\varepsilon_{mech}$=0.5%, O.P. TMF, ΔT=900-1600°F, t_h=90 sec (comp), N_i=218.



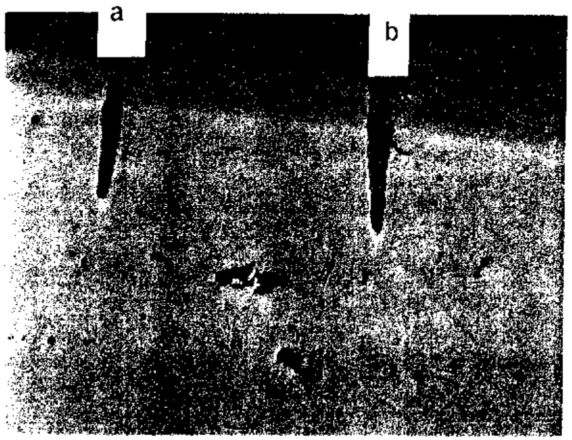
a) Multiple fatigue cracks in aluminide coating surface.



b) Fatigue crack initiation in aluminide coated specimen.

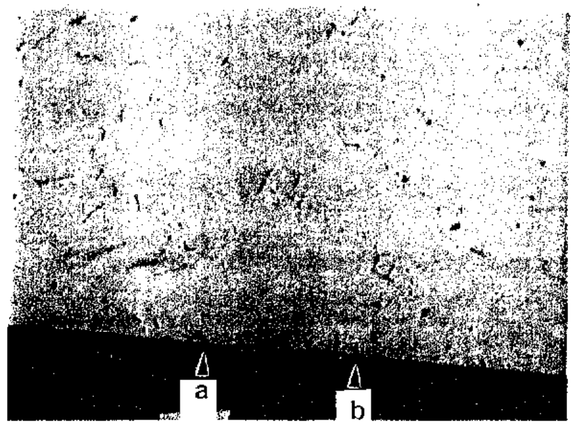
coating

substrate



c) Fatigue crack penetration through aluminide coating and into substrate. Crack depths: a) 5.8 mil (147 μm), b) 6.3 mil (160 μm). (170X)

substrate



d) Small fatigue cracks at uncoated inner wall. Crack depths: a) 0.4 mil (10 μm), b) 0.6 mil (15 μm). (170X)