THERMAL-MECHANICAL FATIGUE LIFE MODEL

FOR COATED SUPERALLOY TURBINE COMPONENTS

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Abstract

Thermal-mechanical fatigue (TMF) cracking can be a life-limiting degradation mode for vanes and blades in gas turbine engines. This paper describes the development of a model which predicts TMF life as a function of materials system, engine component design, and duty cycle parameters. Predicted TMF lives are strongly dependent upon strain range, maximum metal temperature, operating environment, and the material system.

TMF cracking typically initiates in the protective coating that has been applied to inhibit hot corrosion and oxidation of the component. When strain and temperature conditions are sufficient for coating crack penetration into the superalloy, duty cycle dependent oxidation and hot corrosion attack strongly affect the superalloy component's remaining TMF life. Long component lives are predicted for low TMF strain ranges, where the coating remains uncracked or cracks remain confined to the coating.

This TMF life model is unique in that it calculates both mechanical and environmental contributions (transient oxidation and hot corrosion) to coating crack penetration into the superalloy. It is now being used to predict and avoid conditions that can initiate TMF cracks in the coating. It has also provided insight into conditions that have produced TMF cracks in laboratory and field tested engine components.

Introduction

Thermal-mechanical fatigue (TMF) cracking (Figure 1) is a common degradation mode that can necessitate premature removal and repair of turbine engine blades and vanes. Consequently, a life model was developed to predict and avoid this mode of component distress. TMF lives are calculated as a function of coating crack initiation and crack propagation to a critical depth into the component. The following sections review model development and the sensitivity of TMF life to component design parameters, duty cycle, and coating/superalloy properties.
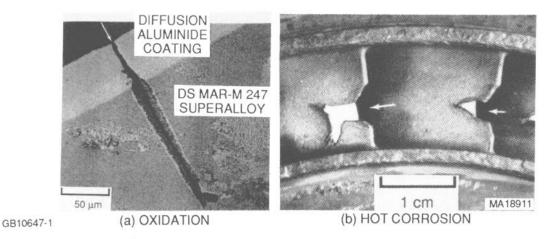

Figure 1. Environmental attack (left: oxidation; right: hot corrosion) contributes to the severity of TMF cracking.

Thermal-Mechanical Fatigue Life Prediction Model

Although it is possible to consider a range of TMF cycle shapes, this paper is focused on analysis of the out-of-phase elastic strain (stress) cycle illustrated in Figure 2. This type of cycle is most commonly found at airfoil locations experiencing TMF cracks. Also, in order to be a versatile design tool, the TMF life model has been developed to facilitate rapid evaluations of design, duty cycle, and material system options that are available early in the component design process. Coating crack initiation and superalloy crack propagation aspects of the model are discussed in the following paragraphs.
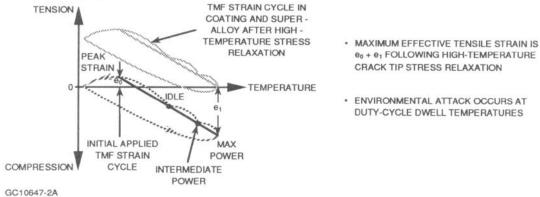

Figure 2. Effective tensile strain (stress) in out-of-phase TMF cycle is increased by high-temperature crack tip stress relaxation.

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Coating Crack Initiation

Cracks typically initiate at airfoil surfaces; i.e., where TMF strain is greatest. Consequently, the cracks initiate in the protective coating applied to achieve acceptable surface stability in an aggressive combustion gas environment. Coating crack initiation is strongly dependent upon the effective tensile strain range. Initiation is modeled as a function of stress relaxation in the coating, effective thermal-mechanical strain range, coating/superalloy thermal expansion mismatch strain, and coating fracture strain and ductility.

Coating Stress Relaxation. Turbine coatings creep at significantly (2 orders of magnitude) lower stresses than superalloys [1-3]. Consequently, coatings cannot support significant loads at high temperatures. Elastic strain (stress) relaxation occurs rapidly (in about 1 second) at a temperature near 1050C. At lower temperature levels (700C), stress relaxation requires about three hours.

For the purpose of the model, the zero strain condition for the coating is set at the high temperature point of the duty cycle that precedes engine idle. This assumption is valid for components with duty cycle temperatures above about 650C, which includes most aircraft engine applications in which coatings are used.

Thermal-Mechanical Strain Range in Coating. As illustrated in Figure 2, the effective tensile thermal-mechanical strain range in the coating is equal to the tensile strain (e_0) plus the compressive strain (e_1), which can be relaxed and converted to a tensile strain.

Thermal Expansion Mismatch Strain. The thermal expansion coefficient of a coating is dependent on its composition. Diffusion aluminide and platinum aluminide coatings will typically have lower thermal expansion coefficients than superalloys.[1,4] Consequently, as the airfoil is cooled from a high temperature duty cycle point, diffusion aluminide coatings are compressed by the greater thermal contraction of the superalloy. The magnitude of the compressive thermal expansion mismatch strain (at room temperature) in a diffusion aluminide coating on a commonly specified superalloy (Mar-M 247), is on the order of 0.1 percent. This compressive mismatch strain increases the measured fracture strain of the coating on superalloy specimens.

In contrast, ductile NiCoCrAlY overlay coatings typically have slightly higher thermal expansion coefficients than the superalloy.[1] Consequently, ductile coatings typically develop tensile thermal expansion mismatch strains during cooling. The value of the coating/superalloy thermal expansion mismatch strain in the coating (e_{cte}) is also dependent upon the elevated temperature duty cycle metal temperature that precedes idle and the temperature at which tensile strain is peaked.

Coating Ductility

Due to their intermetallic matrix, diffusion nickel-aluminide and platinum aluminide coatings are brittle at low temperatures [1,4-6]; i.e., the tensile (single cycle) fracture strain of a diffusion aluminide coating is only a few tenths of a percent at temperatures below about 650C. In contrast, overlay NiCoCrAlY coatings have been developed with improved (1-2 percent) ductility at room temperature.

Coating Crack Initiation Life

Cyclic crack initiation lives of brittle diffusion aluminide coatings have been estimated with the aid of the 'universal slope' of the Mansion-Coffin elastic strain range versus fatigue crack initiation life relationship:

$$\text{Cycles to Initiation} = \left(\frac{e_f}{e_o + e_1 + e_{cte}} \right)^{8.3} \tag{1}$$

Where: e_f is the coating fracture strain at the peak tensile strain temperature, and $e_o + e_1 + e_{cte}$ is the effective tensile strain range in the coating. When the maximum cycle temperature exceeds about 650C, both the e_o and e_1 terms are positive. In contrast, the coating/superalloy coefficient of thermal expansion mismatch strain in the coating, e_{cte}, is typically a negative value for diffusion aluminide coatings on most nickel base superalloys. The negative value of e_{cte} reduces the effective TMF strain range.

NiCoCrAlY and CoCrAlY overlay coatings, with aluminum contents below about 12.5 weight percent, can have increased (1 to 10 percent) ductility in the temperature range where diffusion aluminide coatings are brittle. Low temperature coating ductility can be used to improve the coating resistance to crack initiation.

Two criteria are used to predict the crack initiation life of a ductile overlay coating. The following total fracture strain relationship is used to predict coating crack initiation under high TMF strain conditions:

$$\begin{array}{c}\text{Cycles To Initiation} \\ \text{(Total Strain)}\end{array} = \left(\frac{\text{Ductility} + \text{UTS/E}}{e_o + e_1 + e_{cte}} \right)^{n1} \tag{2}$$

Where: Ductility is the plastic tensile elongation in a tensile test, UTS is the ultimate tensile strength, and E is the elastic modulus. The exponent n1 is 2.8 for a NiCoCrAlY coating containing 12.5 percent aluminum (see Figure 3).

Under low TMF strain conditions, crack initiation in ductile NiCoCrAlY coatings is estimated with an elastic strain criteria that is similar to that used for brittle aluminide coatings; i.e., UTS/E is substituted for the brittle fracture strain of the diffusion aluminide coating.
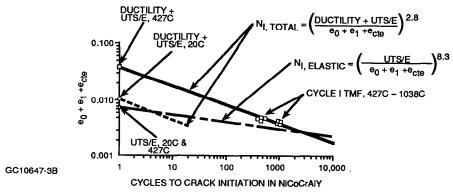

Figure 3. High strain range inititation of TMF cracks in NiCoCrAlY coating is strongly dependent upon ductility and peak strain temperature.

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As indicated in Figure 3, the TMF life model for ductile coatings uses the larger of the two coating crack initiation lives calculated by these two equations. When high TMF strains are present in a component, the predicted coating crack initiation life will be strongly dependent on the peak tensile strain temperature.

Crack Penetration Into The Superalloy

Crack propagation into the superalloy is controlled by both mechanical and environmental crack growth mechanisms. Mechanical propagation is dependent on the effective tensile strain (stress) intensity factor range at the crack tip. Crack extension also ruptures the oxide scale at the crack tip during each cycle and exposes the superalloy to transient oxidation and hot corrosion attack. Mechanical and environmental modes of TMF crack propagation are discussed in the following paragraphs.

Mechanical Crack Propagation

Paris Law. When the environmental contributions to crack propagation are negligible, TMF propagation into the superalloy has been observed to follow Paris Law behavior [7]:

$$da/dN,_{mech.} = A \, K_{eff}^{B} \tag{3}$$

Where: K_{eff} is the effective tensile strain intensity factor range at the crack tip. (The strain intensity factor is a modulus normalized stress intensity factor.) Isothermal da/dN (R=0.05) data obtained at the peak strain temperature or TMF crack propagation data can be used to establish the Paris Law behavior.

Stress Relaxation (Creep) Effects. Leverant, et al.[7] observed that compressive TMF stresses (elastic strains) are stable at low temperatures. In contrast, at temperatures where creep is possible, compressive stresses can be partially or completely relaxed. Analysis of TMF crack propagation data indicates that compressive stresses (e_1) are stable in superalloys at low and moderate temperatures (below about 843C for DS Mar-M 200 + Hf and DS Mar-M 247), but relax rapidly at higher temperatures (above 954C). The effect of stress relaxation on the effective TMF strain range is estimated with the following relationship, which describes the above behavior:

$$e_{eff} = e_o + e_1(-1 + 2[e^{(1.45+1.45\tanh(([T_{max}-T_{sr}]/35.8))}]^{0.238}) \tag{4}$$

Where: T_{max} is the maximum temperature of the TMF cycle, and T_{sr} is the temperature where the initially compressive e_1 elastic strain (stress) has partially relaxed to become half tension and half compression. The value of T_{sr} is dependent upon the temperature capability (creep strength) of the superalloy and is about 899C for DS Mar-M 247. T_{sr} is higher for single-crystal alloys (941C for CMSX-3) and lower for equiaxed superalloys (873C for Mar-M 247).

The above values of T_{sr} are for a TMF test with 0.0055 hour (20 seconds) dwell time at T_{max} per cycle. T_{sr} increases for shorter dwell times and decreases for longer dwell times. The effect of dwell time at the maximum temperature may be estimated using the Larson-Miller Parameter:

$$(T_{sr} + 273)(20 + \log [\text{dwell time}]) = 17.74(T_{sr\ 20s} + 273) \tag{5}$$

Strain Intensity Factor of a Coating Crack. Although coatings are typically weak at high temperatures, nevertheless they can be strong at lower temperatures. Mechanical property data for the NiCoCrAlY coating are comparable to that of a directionally solidified (DS) superalloy for temperatures below 593C. Consequently, a crack in the coating can have a significant strain (stress) intensity factor when tensile stresses peak at low temperatures, which is the case for the TMF cycle under consideration. The strain intensity factor of a coating-initiated TMF crack has been described elsewhere [1].

Environmental Crack Propagation

As previously noted, transient oxidation and hot corrosion are common features at the tips of TMF cracks formed in engines (Figure 1). In fact, for many gas turbine engine conditions, the environmental crack propagation modes are the most important when cracks and associated strain (stress) intensity factors are small; i.e., sufficient to damage the oxide scale at the crack tip.

Threshold for Oxide Scale Damage. Cyclic damage to the brittle crack tip oxide scale occurs when the crack propagates mechanically at low temperatures. Fracture of the crack tip oxide scale during the low temperature portion of the cycle facilitates higher temperature transient oxidation and hot corrosion. The threshold strain intensity factor for oxide scale damage is significantly lower than that usually associated with negligible rates of mechanical crack propagation. Based upon limited data, the threshold strain intensity factor is about 6×10^{-6} meter$^{0.5}$.

Transient Oxidation. At high temperatures, uncoated superalloys are dependent upon the formation of thermally-grown oxide scales for protection against environmental attack. When a bare superalloy surface is first exposed to a high temperature air environment, all of the metallic elements in the alloy can be converted to their oxides. Thermogravimetric data for Mar-M 247 and CMSX-3 indicate that the rate of oxidation is initially linear with respect to time, and then changes to much more protective parabolic growth.[8] The transient period of linear oxidation persisted for 12 to 36 minutes at high temperatures (1100 to 1200C) and for 25 minutes to 2 hours at lower temperatures (900 to 1000C). The temperature dependence of transient (linear) oxidation is very strong, as shown in Figure 4 for Mar-M 247.
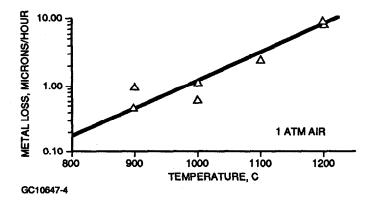

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Figure 4. Transient oxidation rate of Mar-M 247 is strongly
dependent upon temperature.

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The oxide scale at the tip of a fatigue crack is ruptured every cycle that the crack propagates. Consequently, the linear oxidation kinetics apply to the problem of TMF crack propagation. The following relationship describes its contribution to TMF crack growth:

$$\text{Oxidation Crack Growth Rate} = \text{Constant} \ (T + 273)^D \ t \ P. \quad (6)$$

Where: T is the duty cycle, t is the time at the duty cycle temperature, and P is the gas pressure. The value of D is 12 for Mar-M 247.

Hot Corrosion. Unfortunately, transient oxidation may not be the most aggressive form of environmental attack. When an engine is operated at coastal airport locations and low altitudes, hot corrosion attack by molten salt deposits can further increase the rate of TMF crack propagation.

The rate of hot corrosion is predicted with an environmental life model that has been described elsewhere [9]. It is strongly dependent upon engine design factors (gas and metal temperatures, turbine pressure, fuel/air ratio, inlet air filtration efficiency [salt removal]) and mission usage parameters (fuel quality [sulfur content], airport location and altitude [salt in the air], and time at duty cycle points).

Model Sensitivity

Sensitivity of TMF life model predictions to engine design, mission usage, and materials system parameters are reviewed and discussed in the following paragraphs. Due to space limitations, only a single coating system, a 50-micron thickness diffusion aluminide, is considered.

Stress Relaxation

Stability of the compressive crack tip stresses is strongly dependent upon maximum metal temperature in the duty cycle and alloy creep strength. When compressive stress is relaxed, the effective tensile stress (strain) is increased. The effect of maximum cycle temperature on propagation of a crack in a diffusion aluminide coating to a depth of 750 microns into DS Mar-M 247 superalloy is illustrated in Figure 5. For this analysis, the magnitude of e_1 is 5 times the value of e_0. Also, to minimize the environmental contribution to crack propagation rates, the dwell time at maximum cycle temperature was set at 20 seconds.
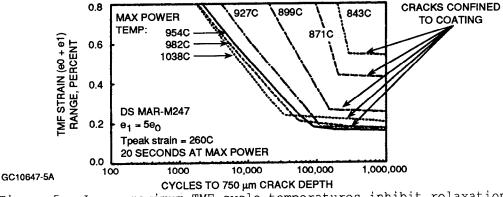

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Figure 5. Lower maximum TMF cycle temperatures inhibit relaxation of compressive strain (stress) and increase crack propagation life.

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Figure 5 indicates that propagation lives decrease rapidly as the maximum temperature increases from 843 to 954C. Also, the model predicts that, when the maximum temperature is below 954C, strain ranges exist where cracks in the diffusion aluminide coating will not propagate into the DS Mar-M 247 superalloy. Non-propagation of coating cracks occurs when the strain intensity factor is below the threshold level (6×10^{-6} meter$^{0.5}$) for damage to the oxide scale at the crack tip. This condition is achieved when the tensile strain (e_0) is small, relaxation of the compressive strain (e_1) is minimal, and the coating/superalloy thermal expansion mismatch strain (stress) in diffusion aluminide coating is compressive.

When the maximum temperature exceeds 954C, the strain range boundary between propagating and non-propagating coating cracks becomes negligible for DS Mar-M 247. This result is attributed to a fully effective (tensile) TMF strain range and an increase in the fracture strain of the coating (a CTE mismatch strain effect).

Overtemperature Effect

Relaxation of compressive stresses in a component is not reversible. Consequently, the strain range for a non-propagating coating crack can be significantly reduced by an overtemperature event. For the predominantly compressive TMF cycle in the previous example, when the maximum temperature was 843C, non-propagating coating cracks were predicted at TMF strain ranges up to 0.66 percent. However, the strain range for non-propagating coating cracks is reduced to 0.2 percent by a 927C overtemperature event.

Mean Strain

In the previous example, compressive strain (e_1) was five times larger than the tensile strain (e_0) of the applied TMF cycle. Relatively long TMF crack propagation lives were predicted for diffusion aluminide coated DS Mar-M 247 specimens tested at low maximum cycle temperatures (843C), where the compressive strain component was stable. However, as indicated in Figure 6, this life advantage is quickly reduced as mean strain becomes zero or tensile. Similarly, the TMF strain range for cracking confined to the coating is reduced when the mean strain becomes tensile.
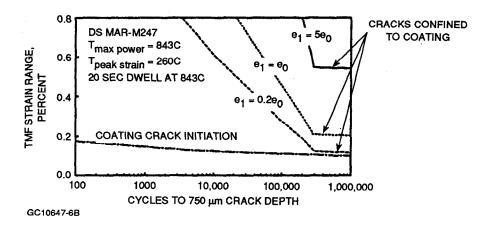

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Figure 6. When stress relaxation is inhibited by low maximum temperatures, mean strain strongly affects TMF crack propagation life.

Although mean strain is predicted to have a large effect on TMF life for lower temperature cycle conditions, it has a negligible effect at higher maximum temperatures (954C), where full relaxation of compressive stress is predicted.

Alloy Creep Strength

Stress relaxation in superalloys is dependent upon composition and microstructure. Consequently, TMF crack propagation life in a component will be strongly influenced by the choice of superalloy. Creep-resistant single-crystal alloys (such as CMSX-3) can have a wider strain zone where coating cracks are non-penetrating. The advantage of the single-crystal alloys is strongly dependent on maximum cycle temperature.

Small differences in lives of CMSX-3 and DS Mar-M 247 are predicted when maximum temperatures are below 843C. Also, small differences in lives are predicted at very high temperatures, where extensive stress relaxation occurs in both of these superalloys.

Environmental Effects on Crack Propagation

Compared with gas turbine engine cycles, the environmental contribution (20 seconds of high temperature oxidation) to TMF crack propagation in the previous examples is modest. Engine cycles are much longer in duration. For example, a typical aircraft engine duty cycle may involve a few minutes at full power and an hour at lower power settings. The severity of the combustion gas environment is also increased by operation at coastal airport locations, where salt is present in the air in significant quantities. Consequently, for strains that would produce innocuous environmental degradation in laboratory LCF tests, severe reduction in life is predicted under engine operating conditions. The environmental effect on TMF crack propagation life is illustrated in Figure 7.
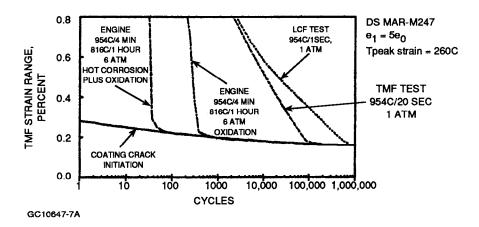

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Figure 7. Environmental attack (oxidation/hot corrosion) reduces TMF crack proagation life.

Coating Crack Initiation

TMF crack initiation in a diffusion aluminide coating occurs at small strains (Figures 6 and 7). Depending upon maximum and minimum cycle temperatures, the crack initiation curves can be raised or lowered by about 0.07 percent strain. This result is achieved because the

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compressive CTE strain in the diffusion aluminide is larger when the airfoil is cooled from a higher maximum temperature (1038C). In contrast, the compressive CTE strain is much smaller when the coating is cooled from a low maximum temperature (704C).

Thermal Barrier Coatings (TBCs)

TBCs insulate air-cooled superalloy turbine airfoils and dramatically reduce metal temperatures (by up to 100C) and thermal strains. In many instances, a 100C reduction in metal temperature is sufficient to reduce or eliminate relaxation of compressive stresses, which inhibits crack propagation. Similarly, TBCs also minimize the severity of transient overtemperature conditions. Lower metal temperatures can dramatically reduce the rate of transient oxidation. TBCs also provide an additional barrier to hot corrosion attack.

Conclusions

1) The TMF life model predicts thermal-mechanical fatigue lives as functions of engine design, mission usage, and materials system parameters.
2) Crack initiation is strongly dependent upon TMF strain range, coating ductility or fracture strain, peak tensile strain temperature, maximum temperature, and coating/superalloy CTE mismatch strain.
3) Environmental attack (oxidation and hot corrosion) significantly accelerates TMF crack propagation into the superalloy.
4) When the coating is cracked, aggressive environmental attack can limit TMF life in engines.
5) A strain range for non-propagating coating cracks can be predicted for conditions of compressive mean strain and low maximum temperatures.
6) Creep-resistant single-crystal alloys can increase the temperature limits for non-propagation of coating cracks.

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