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Damage prediction for un-coated and coated aluminum alloys under thermal and mechanical fatigue loadings based on a modified plastic strain energy approach

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ABSTRACT

In this article, a novel energy-based lifetime prediction model has been presented for uncoated and coated aluminum alloys, subjected to thermal and mechanical fatigue loadings. For this objective, isothermal and thermo-mechanical fatigue tests were performed on the A356.0 alloy, with and without thermal barrier coating systems. This model, which was based on the plastic strain energy, had three correction factors including temperature, strain and mean stress effects. The predicted lifetime showed a proper agreement with experimental data. By the present model, higher accuracy was obtained in comparison to other existed approaches. Besides, the present model had lower number of material constants.

1. Introduction

Thermal barrier coating (TBC) systems have been applied to components of the gas turbine in order to increase the performance. Recently, TBC systems have applications in diesel engines to increase the fatigue lifetime, enhance the thermal efficiency and reduce the fuel consumption and pollutions [1–5]. In mentioned applications, TBC systems are exposed to thermal and mechanical cyclic loadings. Therefore, due to high importance of their service lifetime, scientists have presented different fatigue lifetime prediction models [6–8]. To find advantages and disadvantages of all these models, besides their formulations, a literature review has been mentioned in following paragraphs.

1.1. Sehitoglu's model

As one of famous criteria, the lifetime prediction methodology, proposed by Neu and Sehitoglu [6,7], contains a damage rate model including fatigue, creep and oxidation damages. The pure fatigue mechanism controls the lifetime at low temperatures such as the room temperature (RT). In high-temperatures (HT) low cycle fatigue (LCF) and in-phase (IP) thermo-mechanical fatigue (TMF) loadings, all three damage mechanisms operate. However, during the out-of-phase (OP) TMF test, the oxidation damage becomes significant, whereas the creep mechanism can be negligible [9].

As mentioned, in the Sehitoglu's damage rate model, the total damage (D_{tot}) is considered as the summation of fatigue (D_{fat}), creep (D_{cr}) and oxidation (D_{ox}) damages. The formulation of this model is shown as follows [8],

$$D_{tot} = D_{fat} + D_{ox} + D_{cr} \tag{1}$$

$$\frac{1}{N_{tot}} = \frac{1}{N_{fat}} + \frac{1}{N_{ox}} + \frac{1}{N_{cr}} \tag{2}$$

In which, N_{tot}, N_{fat}, N_{cr} and N_{ox} are total, fatigue, creep and oxidation lifetimes, respectively. When the total damage is equal to unity, the failure occurs. The fatigue damage is represented by fatigue mechanisms that occur at low temperatures.

The strain–lifetime relationship is utilized to estimate the pure fatigue damage component. This relation is written as follows [8],

$$\frac{\Delta\varepsilon_{mech}}{2} = \frac{\sigma'_f}{E}(2N_{fat})^b + \varepsilon'_f(2N_{fat})^c \tag{3}$$

In which, $\sigma'_f, E, b, \varepsilon'_f, c$ are material constants. These material constants can be determined from low-temperature isothermal fatigue tests.

The oxidation damage in the material is defined as follows [8],

$$\frac{1}{N_{ox}} = \left[\frac{h_c\delta_0}{B\phi^{ox}K_{p,eff}}\right]^{-1/\beta} \frac{2(\Delta\varepsilon_{mech})^{1+2/\beta}}{(\dot{\varepsilon}_{mech})^{1-\alpha/\beta}} \tag{4}$$

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In which, h_c is a critical oxide length, δ_0 is the ductility of the environment effected material, ϕ^{ox} is the phasing factor for the environmental damage, $K_{p,eff}$ is the effective parabolic oxidation constant and B, α, β are constants. In Eq. (4), the mechanical strain range and the mechanical strain rate are shown with $\Delta\varepsilon_{mech}$ and $\dot{\varepsilon}_{mech}$, respectively.

It should be mentioned that when there are coating layers (even for short-term and long-term protections) in components, the oxidation damage would be occurred in the substrate alloy after the complete failure in coating layers.

The effective parabolic constant is defined as follows [8],

$$K_{p,eff} = \frac{1}{t_c}\int_0^{t_c} D_0 \exp\left(\frac{-Q}{RT(t)}\right) dt \tag{5}$$

where t_c is the period of the cycle, D_0 is the diffusion coefficient, Q is the activation energy for the oxidation, R is the universal gas constant, and $T(t)$ is the temperature as a function of the time. The phasing factor is introduced to quantify the relative oxidation damage between phasings. This parameter is defined as follows [8],

$$\phi^{ox} = \frac{1}{t_c}\int_0^{t_c} \exp\left(-\frac{1}{2}\left[\frac{1+\dot{\varepsilon}_{th}/\dot{\varepsilon}_{mech}}{\xi^{ox}}\right]^2\right) dt \tag{6}$$

In which, $\dot{\varepsilon}_{th}$ and $\dot{\varepsilon}_{mech}$ are thermal and mechanical strain rates, respectively. This form of the phasing factor is chosen to represent observed severity of oxide cracking for different conditions. The parameter ξ^{ox} is a measure of the relative amount of the oxidation damage for different thermal to mechanical strain ratios.

The oxidation damage equation is revised by incorporating a new function $(1/\Psi)$ to reflect the protective role of coating layers against the pure environmental attack. The oxidation damage equation for the TBC system can be written as follows [8],

$$\frac{1}{N_{ox}} = \left[\frac{h_c\delta_0}{B\phi^{ox}K_{p,eff}}\right]^{-1/\beta} \frac{2(\Delta\varepsilon_{mech})^{1+2/\beta}}{(\dot{\varepsilon}_{mech})^{(1-\alpha/\beta)1/\Psi}} \tag{7}$$

In which, $\Psi \to 1$ is for the short-term coating protection and $\Psi \to \infty$ is for the long-term coating protection. Although Ψ is expected to be a function of experimental variables such as the strain range ($\Delta\varepsilon_{mech}$), the strain rate ($\dot{\varepsilon}$), the maximum temperature (T_{max}) and the coating character. For the simplicity, it is taken as follows [8],

$$\Psi = \Psi_1(\Delta\varepsilon_{mech}, T_{max}, \dot{\varepsilon}) = \frac{r_0}{\Delta\varepsilon_{mech}} \tag{8}$$

where r_0 is a constant. This constant is a function of the maximum temperature and the strain rate.

The total creep damage is obtained by integrating the creep damage in each cycle throughout the fatigue lifetime of the material. Its relation can be written as follows [8],

$$\frac{1}{N_{cr}} = \phi^{cr}\int_0^{t_c} A \exp\left(\frac{-\Delta H}{RT(t)}\right)\left(\frac{\alpha_1\bar{\sigma} + \alpha_2\sigma_h}{K}\right)^m dt \tag{9}$$

where ϕ^{cr} is the phasing factor for the creep, ΔH is the activation energy for the rate-controlled creep mechanism, $\bar{\sigma}$ is the effective stress, σ_h is the hydrostatic stress, and K is the drag stress. The constants α_1, α_2 account for the degree of the damage occurring under tensile and compressive loads.

The form of the creep phasing factor is the same as the oxidation phasing factor, as follows [8],

$$\phi^{cr} = \frac{1}{t_c}\int_0^{t_c} \exp\left(-\frac{1}{2}\left[\frac{-1+\dot{\varepsilon}_{th}/\dot{\varepsilon}_{mech}}{\xi^{cr}}\right]^2\right) dt \tag{10}$$

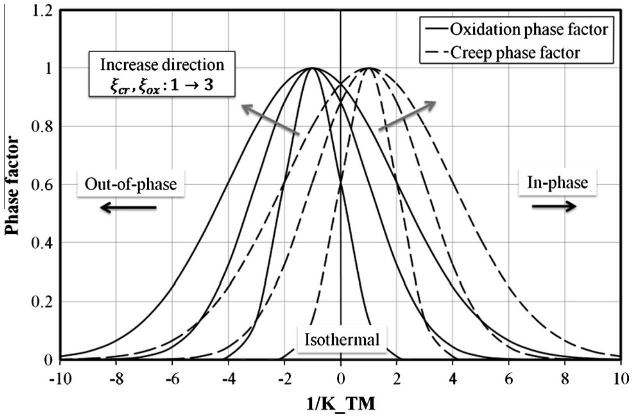

Fig. 1. Creep and oxidation phasing factors based on K_{TM} values.

In which, the parameter ξ^{cr} is a measure of the relative amount of the creep damage for different thermal to mechanical strain ratios. Phasing factors are shown in Fig. 1 under IP, OP and isothermal fatigue loadings versus the constraint factor or the thermo-mechanical loading factor (K_{TM}). In TMF tests, since both thermal and mechanical strains change during cycles, K_{TM} is defined as the ratio of the mechanical strain amplitude to the thermal strain amplitude. This factor is as follows,

$$K_{TM} = \frac{\varepsilon_{a,mech}}{\varepsilon_{a,th}} \tag{11}$$

where $\varepsilon_{a,mech}$ and $\varepsilon_{a,th}$ are mechanical and thermal strain amplitudes.

This model has been successfully employed in the fatigue lifetime prediction of 1070 steel [7] and a nickel-based superalloy, Mar-M247 [10,11]. In addition, this model was revised to estimate the fatigue lifetime of coated materials, such as an aluminide coated Mar-M247 [8]. It can be said that this model has been well introduced and it has high accuracy. Besides, it has been widely used in commercial softwares, such as the FEMFAT code. However, the interaction between damages is not considered in this model. Then also, if the HT-LCF lifetime of materials becomes more than their RT-LCF lifetime, the Sehitoglu's model will have no application in these cases.

1.2. Classical models

Several other researchers have been applied classical theories including Manson–Conffin–Basquin (MCB) and Smith–Watson–Topper (SWT) criteria to model the fatigue lifetime of TBC systems. In general, these models have low accuracy with a high scatter band. In following sentences, several examples have been mentioned.

Julis et al. [12] and Sahu et al. [13] used the MCB approach for an Al–Si diffusion coated Inconel 713LC and a titanium alloy (IMI-834) with titanium aluminide coating, respectively. Julis et al. [12] performed LCF tests on cylindrical specimens at 800 °C in the air. They illustrated fatigue life improvements while using coating layers, by using the MCB approach. Sahu et al. [13] compared the LCF behavior of a titanium alloy in the bare condition and with titanium aluminide coating, at 600 °C in the air. By using the MCB model, they demonstrated that at higher values of total strain amplitudes, coated alloys had longer fatigue lifetime, as compared to bare alloys. However, at lower values of total strain amplitudes, coating layers seemed to have no effect on the fatigue lifetime. Rauch and Roos [14] utilized the SWT approach to analyze turbine components at a typical local service temperature of 600 °C. They developed a new lifetime assessment method based on the SWT damage parameter, which was a function of the accumulated plastic strain. As other approaches, Traeger et al. [15]