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Mitigating time-dependent crack growth in Ni-base superalloy components

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ABSTRACT

Advanced Ni-based gas turbine disks are expected to operate at higher service temperatures in aggressive environments for longer time durations. Exposures of Ni-base alloys to these aggressive environments can lead to cycle-dependent and time-dependent crack growth in superalloy components for advanced turbopropulsion systems. In this article, the effects of tertiary γ' on the crack-tip stress relaxation process, oxide fracture and time-dependent crack growth kinetics are treated in a micromechanical model which is then incorporated into the DARWIN® probabilistic life-prediction code. Using the enhanced risk analysis tool and material constants calibrated to powder-metallurgy (PM) disk alloy ME3, the effects of grain size and tertiary γ' size on combined *time-dependent* and *cycle-dependent* crack growth in a PM Ni-alloy disk is demonstrated for a generic rotor design and a realistic mission profile using DARWIN. The results of this investigation are utilized to assess the effects of controlling grain size and γ' size on the risk of disk fracture and to identify possible means for mitigating time-dependent crack growth (TDCG) in hot-section components.

1. Introduction

Hot-section components in advanced turbopropulsion systems are expected to operate at higher heat dwell conditions for longer time durations than those in current service conditions. Under high heat dwell environments, advanced Ni-base superalloys intended for engine disk applications may be susceptible to concurrent time-dependent damage modes such as oxidation, stress corrosion, and creep in additional to cycle-dependent fatigue crack initiation and growth, which often manifest synergetic interaction effects on crack growth rates. Current life-prediction methodologies, however, generally do not treat synergetic interactions of multiple damage modes on component life reliability. Thus, there is a need to develop a probabilistic time-dependent fracture mechanics analysis capability for treating multiple damage modes in advanced Ni-based alloys for operations with long duration at high temperatures where time-dependent degradation mechanisms such as creep, oxidation, corrosion, and stress rupture may compete with time-independent fatigue crack growth as the component life-limiting mechanism [1,2]. On the other hand, advanced processing techniques and heat-treatment procedures have also been developed to create tailored microstructures in gas turbine disks. It is now possible to fabricate powder-metallurgy turboengine disks with controlled grain size and gamma prime sizes in the bore, rim, and transition zone of advanced Ni-base superalloys such as LSHR [3–5]. These advances in processing and heat-treatment techniques provide a new avenue for designing local microstructures with location-specific properties to combat and mitigate cycle-dependent and time-dependent crack growth mechanisms that are operative at high-dwell environments through an integrated computational design, processing, life-prediction, and risk assessment route.

This article focuses on the development of a fracture mechanics life-prediction methodology that can be utilized in two ways: (1) to treat multiple damage mechanisms pertinent for high-heat dwell environments in turboengine systems, and (2) to serve as a life-prediction and risk assessment tool in an integrated computational design and manufacturing platform [1,2]. To achieve this ultimate objective, a generic fracture mechanics approach has been implemented in a probabilistic life-prediction code, DARWIN [6], to treat the interaction of cycle-based and time-based crack growth resulting from various fatigue and fracture mechanisms, including those involving environmental degradation mechanisms such as oxidation, corrosion, stress rupture and creep. In this approach, cycle-dependent fatigue crack growth and time-dependent crack growth are treated as two independent processes

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whose crack growth increment, da, over a mission can be summed according to the expression given by [7–9]

$$(da)_{mission} = \left(\frac{da}{dN}\right)_{cyclic} dN + \left(\frac{da}{dt}\right) dt \tag{1}$$

where the first term on the right-hand-side of Eq. (1) treats cycle-dependent crack growth while the second term treats time-dependent crack growth for an arbitrary loading history within a mission. For fatigue crack growth test data generated under a constant frequency with dwell (as in dwell fatigue tests), Eq. (1) can be expressed as [7–9]

$$\left(\frac{da}{dN}\right)_{dwell} = \left(\frac{da}{dN}\right)_{cyclic} + \left[t_d + \frac{1}{f}\right]\left(\frac{da}{dt}\right) \tag{2}$$

where t_d is the dwell time and f is the frequency of the dwell fatigue cycles. To obtain the crack growth life, Eq. (2) is integrated over the fatigue cycle. The fatigue crack growth rate, da/dN, can be represented in terms of the Paris power-law [10] or a microstructure-based version [11], as given by

$$\frac{da}{dN} = A\Delta K^n \quad \text{for } \Delta K > \Delta K_{th} \tag{3}$$

where ΔK is the stress intensity range, ΔK_{th} is the large-crack crack growth threshold, and A and n are material constants. Cyclic crack growth generally follows a transgranular path, while time-dependent crack growth due to stress-assisted grain boundary oxidation typically follows an intergranular path [12–16]. The transition from transgranular fracture to intergranular fracture depends on the temperature, load frequency, and hold time. In general, time-dependent crack growth under K-controlled conditions can be expressed as [9,17,18]

$$\frac{da}{dt} = B_o \exp\left(-\frac{Q}{RT}\right) K^m \quad \text{with } m > 0 \text{ and } K > K_{th} \tag{4}$$

where K_{th} is the static crack growth threshold and B_o is a material constant which can be determined empirically from experimental data or evaluated from micromechanical models that relate B_o to material parameters. Both types of time-dependent crack growth models have been developed and reported in earlier publications [9,17]. For oxidation-induced crack growth, da/dt is described by [17]

$$\frac{da}{dt} = \frac{s_o}{t_o}\left(\frac{\pi E}{2\sigma_y \varepsilon_f^*}\right)^{m/2}\left(\frac{1}{E\sqrt{\pi d_o}}\right)^m \left(\frac{D_o}{D}\right)^{m\gamma/2} \times \exp\left(-\frac{Q}{RT}\right) K^m \quad \text{with } m > 0 \text{ and } K > K_{th} \tag{5}$$

where E is Young's modulus, σ_y is the yield stress, s_o is the reference penetration distance, t_o is the reference time, d_o is the reference crack-tip element size, D_o is the reference grain size, D is the grain size, m is the crack growth exponent, Q is the activation energy, R is the universal gas constant, T is the absolute temperature, and γ is the grain size exponent. Eq. (5) can be expressed in the form of Eq. (4) with B_o serving as a material constant that incorporates all material-related parameters. For the microstructure-based model, the material constant B_o is given by [17]

$$B_o = \frac{s_o}{t_o}\left(\frac{\pi E}{2\sigma_y \varepsilon_f^*}\right)^{m/2}\left(\frac{1}{E\sqrt{\pi d_o}}\right)^m \left(\frac{D_o}{D}\right)^{m\gamma/2} \tag{6}$$

which depends on the underlying microstructure but not on the temperature, stress or the stress intensity factor, K. Details of the derivation for Eq. (5) including a validation of the grain size dependence can be found in a recent publication [17].

The objective of this article is to report the development of a time-dependent crack growth for treating the effects of creep stress relaxation at the crack tip on time-dependent crack growth in Ni-based superalloys. The micromechanical crack growth model is then implemented into DARWIN [3] and the methodology is utilized to perform life-prediction and risk assessment for a fictitious engine disk made from a powder metallurgy alloy ME3, also referred to as Rene 104, with a designed microstructure of controlled grain size and tertiary gamma size. The development of the time-dependent crack growth model for treating oxidation-induced crack growth under small-scale creep conditions is presented in Section 2. Applications of the time-dependent crack growth model to treat the cycle-dependent and time-dependent crack growth response of ME3 are described in Section 3. Using the enhanced risk analysis tool and material constants calibrated to powder-metallurgy (PM) disk alloy ME3, the effects of grain size and tertiary γ' size on combined *time-dependent* and *cycle-dependent* crack growth in a fictitious ME3 disk is demonstrated in Section 4 for a generic rotor design and a realistic mission profile using the DARWIN. In Section 5, the results of this investigation are utilized to assess the effects of controlling grain size and tertiary γ' size on the risk of disk fracture and to identify possible means for mitigating time-dependent crack growth in hot-section components. The computational results demonstrate that controlling location-specific microstructures and properties (e.g., instigating coarse grains and coarse tertiary γ' in the rim) can be an effective means of enhancing disk life and reducing fracture risk.

2. Development of oxidation-induced crack growth model with crack-tip stress relaxation

The effects of crack-tip stress relaxation on the time-dependent crack growth rate, da/dt, response equation was investigated by considering the fracture process of the crack-tip oxide layer with and without stress relaxation at the crack tip, as shown in Fig. 1. It is envisioned that stress relaxation at the crack tip can be described in term of the transient creep, $C(t)$, field [19] that is embedded inside the K-field. For transient creep, the near-tip stresses in the y-direction normal to the crack is given by [19].

$$\sigma_{yy} = \left[\frac{C(t)}{I_n A r}\right]^{1/(n+1)} \tag{7}$$

where n is the creep exponent, $C(t)$ is the time-dependent energy integral, I_n is a normalization parameter, A is the power-law creep coefficient, and r is distance ahead of the crack tip. The corresponding stresses in the K-field are given by [20]

$$\sigma_{yy} = \frac{K}{\sqrt{2\pi r}} \tag{8}$$

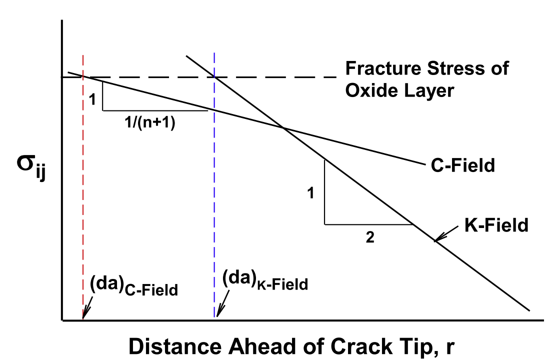

Fig. 1. Schematics of the oxide fracture process in the C-field compared to oxide fracture in the K-field. Stress relaxation at the crack tip reduces the da/dt response because the relaxed stress field is less likely to cause oxide fracture at the crack tip by decreasing the region where the critical stress for oxide fracture can be attained.