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Probabilistic evaluation on fatigue crack growth behavior in nickel based GH4169 superalloy through experimental data

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ABSTRACT

The present paper developed a stochastic model to evaluate the scatter in fatigue crack growth (FCG) behavior of turbine disc GH4169 superalloy. Model parameters were calculated based on systematic experiments on compact tension (CT) specimens cut from the rim and installation flange locations of a turbine disk at corresponding service temperatures with stress ratios of 0.1 and 0.5. Based on the experimental data, piecewise FASTRAN model combined with Dugdale strip-yield model that includes the crack closure effect in GH4169 superalloy were proposed to formulate the deterministic FCG model. The probabilistic distribution of FCG rate was represented by a life distribution factor (LDF), combined with the deterministic model. Modeling results revealed that the variance of FCG rate followed a decrease-to-increase trend as crack propagates, which was consistent with the microstructural dependence of FCG revealed in typical polycrystalline materials. Proposed probabilistic model effectively reflected the stochastic property of FCG, offering a promising tool for probabilistic damage tolerance assessment (DTA).

1. Introduction

Turbine disc, a critical rotating component of an aero-engine, experiences significant level of mechanical and thermal stresses induced by centrifugal loading and temperature gradient, respectively. Fatigue properties of materials should be systematically investigated to obtain reliable design of turbine disc. Safe-life principle was employed in critical systems that are difficult to repair or may cause severe damage, requiring an extremely low level of risk based on testing and analysis data. However, this technique considered the most dangerous state of the engines, contributing to an over-conservative design thereby requiring more resources than those are actually needed. After the catastrophe happened in Sioux City, 1989, which was due to a fatigue crack originating from a critical area of the stage I fan disc [1], damage tolerance assessment (DTA) became a required procedure for the life-limited parts in aircraft engine [2,3]. This approach is used to manage crack extension in structures through application of fracture mechanics. Therefore, one of the core contents in DTA is to identify the materials resistance to crack growth.

Nickel based superalloys, e.g., GH4169 superalloy studied here, are usually used in high temperature turbine discs for their unique combination of microstructural stability and fatigue resistance, due to the high volume fraction of precipitates γ'/γ'' that uniformly distribute in disordered γ phases [4,5]. Because of the unavoidable instability of heat treatment procedure, material

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Nomenclature

a	actual crack length
c	physical crack length including physical crack and cyclic-plastic-zone size
$\bar{d}$	average grain size
da/dN	fatigue crack growth rate
f	frequency
h	fitting parameter relating crack opening to maximum stress intensity factors
i	number of divided interval in probabilistic model establishment
k, λ	shape and scale parameters in Weibull distribution
q	empirical constant in FASTRAN model
r_p	plastic zone size
α	normalized crack length to specimen width
σ_{ys}	yield strength
σ_u	ultimate tensile strength
μ_i, σ_i	mean and standard variance of LDF in interval i
B, W	specimen thickness and width
C_i, n_i	fitting parameters for each segment in FASTRAN model
$F(\alpha)$	general boundary-correction factor
$G(\alpha)$	modified boundary-correction factor for compact tension specimen
K_F, m	fracture parameters
K_{Ie}	elastic stress intensity factor at failure
K_{max}	maximum stress intensity factor
K_{max}^a	maximum stress intensity factor calculated from the actual crack length a
K_{op}	crack opening stress intensity factor
N	number of cycles
P_{max}	maximum tensile load
P_{op}	threshold load that terminates crack closure
R	radius of sampling turbine disc
R_{cor}^2	correlation coefficient
R_σ	stress ratio
S_{max}	maximum applied stress
S_{op}	crack opening stress
S_u	plastic-hinge stress
T	temperature
$X_{L,i}^j$	life distribution factor for specimen j at interval i
Δr_p	cyclic-plastic-zone size
ΔK^a	amplitude of stress intensity factor calculated by actual crack length a
ΔK_{eff}	effective stress intensity factor

performance turns out to be scattered, including the fatigue crack growth (FCG) resistance. Thus, probabilistic models should be established to obtain accurate prediction on fatigue life of turbine discs.

The probabilistic FCG models are usually derived from the deterministic FCG models, with a probabilistic process of parameters fitted from experimental data. However, since the deterministic FCG models always include more than one parameter to be fitted [6–11], corresponding probabilistic models are usually difficult to implement in engineering problems since a complex joint probability density function should be established. To overcome this limitation, a random factor, derived from stochastic variable or experimental condition, was employed to generalize the model for broader utilizations [12–16]. It has been reported that such model can effectively align the scattering nature of experimental data to the probabilistic FCG model. On the other hand, a realistic probabilistic FCG model should also include a reliable mechanism on material failure during crack extension, aiming at a more convincible tool for fatigue life prediction.

In previous study [17], we have conducted systematic experiments on the FCG performance of the GH4169 superalloy. It was found that a macroscopic crack closure effect plays a critical role in determining the dependence of FCG on the grain size. Therefore, to develop a probabilistic FCG model for GH4169, the effective stress intensity factor (SIF) ΔK_{eff} by incorporating the effect of crack closure needs to be calculated.

Several numerical models of plasticity-induced crack closure (PICC) have been developed for the calculation of ΔK_{eff}, such as the FAtigue crack growth STRuctural ANalysis (FASTRAN) model by Newman [18–20] and the European Space Agency (ESA) model by de Koning et al. [21]. They have been integrated into the NASGRO software, which was designed for fatigue life prediction of engineering components. The primary difference between these two models lies in the determination of constraint factors, concerning about the stress state around the crack. Irwin [22], Rice [23], Dugdale [24], and McClung [25] have proposed their models for the correction of crack length with forward or reversed plastic zone size. Although these models presented good agreement with experimental data from fatigue tests on different materials, work is needed to establish a probabilistic FCG model that includes the crack closure effect for GH4169 superalloy.

In this paper, systematic experiments for the materials of the GH4169 superalloys at different locations, corresponding service temperatures, and different stress ratios were conducted to calculate the stochastic FCG performance. Based on the experimental data, probabilistic FCG model under the consideration of crack closure was established. Contents are organized as follows. In Section 2, material properties and experimental procedures are presented. In Section 3, the detailed development of the probabilistic model is introduced. Section 4 presents the results and discussion based on both the experiments and the model. The paper is concluded in Section 5.

2. Material and experimental procedure

2.1. Material

The chemical composition of the GH4169 superalloy include: C (0.035 wt%); Si (0.08 wt%); Mn (0.03 wt%); S (0.003 wt%); P (0.006 wt%); Cr (18.93 wt%); Mo (3.02 wt%); Ti (1.03 wt%); Nb (5.11 wt%); Al (0.53 wt%); B (0.003 wt%); Co (0.08 wt%); Fe (19.46 wt%); balance Ni. The superalloy was cut from an actual turbine disc.