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A viscoplastic study of crack-tip deformation and crack growth in a nickel-based superalloy at elevated temperature

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ABSTRACT

Viscoplastic crack-tip deformation behaviour in a nickel-based superalloy at elevated temperature has been studied for both stationary and growing cracks in a compact tension (CT) specimen using the finite element method. The material behaviour was described by a unified viscoplastic constitutive model with non-linear kinematic and isotropic hardening rules, and implemented in the finite element software ABAQUS via a user-defined material subroutine (UMAT). Finite element analyses for stationary cracks showed distinctive strain ratchetting behaviour near the crack tip at selected load ratios, leading to progressive accumulation of tensile strain normal to the crack-growth plane. Results also showed that low frequencies and superimposed hold periods at peak loads significantly enhanced strain accumulation at crack tip. Finite element simulation of crack growth was carried out under a constant ΔK-controlled loading condition, again ratchetting was observed ahead of the crack tip, similar to that for stationary cracks.

A crack-growth criterion based on strain accumulation is proposed where a crack is assumed to grow when the accumulated strain ahead of the crack tip reaches a critical value over a characteristic distance. The criterion has been utilized in the prediction of crack-growth rates in a CT specimen at selected loading ranges, frequencies and dwell periods, and the predictions were compared with the experimental results.

1. Introduction

Attempts at a mechanistic understanding of fatigue crack propagation may be traced back to Rice (1967) with his seminal analysis on the stress and strain fields near an idealized stationary crack tip under tensile and anti-plane shear cyclic loadings. It was revealed that the cyclic plastic deformation near a crack tip might be entirely determined by the variation in the stress intensity factor, and the reversed plastic-zone size due to the load reversal is one quarter of the size of the maximum plastic zone. Since then, a substantial body of research work has been carried out to study the crack-tip mechanics in order to shed light on the controlling parameter of crack propagation, which includes the well-known Hutchinson–Rice–Rosengren (HRR) field for power-law hardening materials and the RR (Riedel and Rice, 1980) and the HR (Hui and Riedel, 1981) fields for power-law creep materials. Crack-growth simulation has also been extensively carried out to study the crack-growth pattern and the crack-tip plasticity using the finite element method with cyclic plasticity and/or creep models (e.g., Sehitoglu and Sun, 1991; Pommier and Bompard, 2000; Zhao et al., 2001; Tvergaard, 2004).

Viscoplasticity or time-dependent inelastic material behaviour has been shown to play a critical role in crack-tip deformation for materials subjected to cyclic loading at elevated temperature. Keck et al. (1985) demonstrated the

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dependency of crack-tip stress–strain field and plastic-zone size on loading frequency and hold time at the maximum load, where decreased frequency and introduced hold time led to increased crack-tip deformation and plastic-zone size. Finite element simulation of fatigue crack growth by Sehitoglu and Sun (1989) showed that effective stress range and crack opening level strongly depend on time-dependent constitutive relationship. Increased effective stress range and decreased crack opening level were observed when hold period was introduced at the maximum stress. Sung and Liou (1993) analytically studied the near-tip fields for transient crack growth in a viscoplastic solid under small-scale yielding conditions, where the crack-tip fields were shown to depend on both time and crack propagation speed. Experimental and numerical work by Qian et al. (1996) showed marked effects of loading frequency on crack-growth rate, stresses and viscoplastic strains. Andersson et al. (2001) studied fatigue crack propagation in a nickel alloy, IN718, and showed immediate crack opening upon load reversal from the minimum load, suggesting a lack of crack closure for the cases examined.

Nickel-based superalloys have been used for gas turbine discs which are subjected to variable centrifugal and thermal stresses with operation temperatures up to 700 °C. Failure of turbine discs due to the interaction of fatigue, creep and environmental effects can lead to the loss of aircraft. Alloy RR1000 is one of the latest fine-grained nickel-based superalloys, developed at Rolls-Royce Plc of the UK through a powder metallurgy process, to meet the increasing demand of mechanical performance for turbine discs in the latest Trent 1000 Rolls-Royce aero engines. Fatigue and creep behaviour of Alloy RR1000 at elevated temperature have been systematically studied through crack-growth testing using compact tension (CT) and corner notch (CN) specimens. Tong et al. (2001) showed that mixed time and cycle-dependent crack growth seems to be the dominant crack-growth mode for RR1000 at 650 °C. Knowles and Hunt (2002) investigated the influence of microstructure and environment on crack-growth behaviour of RR1000 at 725 °C. Both environment and exposure-induced sigma-phase precipitation at grain boundaries were shown to increase the crack-growth rate through increased crack-tip cavity nucleation, whilst rapid near-tip stress relaxation induced by γ' coarsening has a beneficial effect on the severity of crack-tip cavity damage. For short crack growth at elevated temperature, Pang and Reed (2003) showed that RR1000 demonstrated superior fatigue performance compared to Udimet 720 and was attributed to the benefit of stress relaxation due to its alloy chemistry. Most recently, Dalby and Tong (2005) systematically studied the crack-growth behaviour for RR1000 at elevated temperature by considering a range of loading waveforms and frequencies. Accelerated crack-growth rates were observed in specimens tested at low frequencies, long dwell periods or under slow-fast loading waveform.

Comprehensive experimental and analytical studies (Zhan and Tong, 2007a, b) have also been carried out towards a fundamental understanding of time-dependent deformation behaviour using material constitutive models. Strain-controlled cyclic tests were carried out at 650 °C for selected strain ratio, range and rate. A unified viscoplastic model (Chaboche, 1989) was adopted and modified to describe the time-dependent constitutive behaviour of RR1000 alloy, with model parameters determined from an optimization of the basic monotonic, cyclic and creep experimental data (Zhan and Tong, 2007a, b).

Although viscoplastic constitutive models are available, such information has seldom been fully utilized in the studies of crack-tip mechanics, where a relationship between crack-tip deformation and crack-growth behaviour may be obtained towards a mechanistic characterization of crack growth, as opposed to empirical or semi-empirical models that require extensive experimental data. The main objective of this work is to study the fundamental deformation behaviour near a crack tip in alloy RR1000 at elevated temperature, using the viscoplastic constitutive model presented in Zhan and Tong (2007a, b). Detailed finite element analyses were carried out to study the stress–strain fields near a stationary and a growing crack tip in a CT specimen under mode I cyclic loading conditions. The evolution of the stress and strain fields near a stationary crack tip was obtained and analysed, and the influence of load ratio, loading frequency and dwell period on the evolution of crack-tip stress–strain field was evaluated. Fatigue crack growth was also simulated under a constant ΔK-controlled condition using a node release algorithm. A damage parameter based on crack-tip strain accumulation was identified from which a crack-growth criterion was proposed. Using the proposed criterion, crack-growth rates were predicted for selected loading ranges, frequencies and superimposed dwell times, and compared with those obtained experimentally.

2. The material model

The material model is essentially the unified constitutive equations developed by Chaboche (1989), where both isotropic (R) and kinematic ($\boldsymbol{\alpha}$) hardening variables are considered during the transient and saturated stages of cyclic response. Within the small-strain hypothesis, the strain rate tensor $\dot{\boldsymbol{\varepsilon}}$ is partitioned additively into an elastic part $\dot{\boldsymbol{\varepsilon}}_{\mathrm{e}}$ and an inelastic part $\dot{\boldsymbol{\varepsilon}}_{\mathrm{p}}$:

$$\dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}_{\mathrm{e}} + \dot{\boldsymbol{\varepsilon}}_{\mathrm{p}}. \tag{1}$$

It is assumed that the elastic strain $\boldsymbol{\varepsilon}_{\mathrm{e}}$ obeys the Hooke's law,

$$\dot{\boldsymbol{\varepsilon}}_{\mathrm{e}} = \frac{1+\nu}{E}\dot{\boldsymbol{\sigma}} - \frac{\nu}{E}(\mathrm{tr}\,\dot{\boldsymbol{\sigma}})I, \tag{2}$$