TRANSIENT CREEP-FATIGUE CRACK GROWTH IN CREEP-DUCTILE AND CREEP-BRITTLE MATERIALS: APPLICATION TO ALLOY 617 AND ALLOY 718

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Abstract

Creep-fatigue crack growth is an important failure mechanism for materials operating at high temperatures. While crack growth laws have been developed for hold-time loads and constant-amplitude cyclic loads, load transients must also be considered for determining component lifetimes. In this study, computational fracture mechanics simulations are used to study crack growth in two nickel-base superalloys at elevated temperatures following overloads. The computations demonstrate that post-overload crack growth depends strongly on the magnitude of crack-tip viscoplastic deformation in the bulk material. In some cases, a classical retardation effect is absent. Dynamic recovery and hardening due to viscoplastic strain gradients are also shown to influence post-overload crack-tip fields and crack growth.

1. Introduction

Nickel-base superalloys are widely used in high-temperature applications, including aircraft and land-based turbine engines and power generation. Components are typically subjected to combinations of cyclic loads, sustained loads, and load transients like overloads (OLs) and multi-step hold times. Load transients can arise under design conditions (e.g., load following requirements for power plants) and due to load excursions (e.g., turbulence in an aircraft).

This study is motivated by crack growth experiments with OLs on two nickel-base superalloys: Alloy 617 and Alloy 718. Alloy 617 is a solid solution strengthened alloy proposed for use in the heat exchanger of next-generation nuclear power plants. Alloy 617 is characterized as a creep-ductile material, meaning that widespread viscoplastic deformation occurs during crack growth. However, crack growth experiments at 800°C demonstrate little to no crack growth retardation following OLs. This behavior is more characteristic of *brittle* materials. Alloy 718 is a precipitation hardened alloy used in a variety of applications up to 650°C. Alloy 718 is characterized as a creep-brittle material, meaning that a small viscoplastic zone grows together with an advancing crack. However, significant crack growth retardation occurs following OLs, behavior that is more characteristic of *ductile* materials. In each case, transient crack growth behavior appears to contradict insights gained from steady-state crack growth.

To address this contradiction, creep-fatigue crack growth is investigated in this study using a computational fracture mechanics model. The model combines a viscoplastic constitutive law for the bulk material with an irreversible cohesive zone formulation that captures material degradation due to fatigue and creep. The model is implemented in an incremental finite element framework; crack growth is then an outcome of the boundary value problem. The simulations thereby enable analysis of the transient crack tip fields and crack growth rates during and after OLs with arbitrary loading waveforms.

2. Results

First, a parametric study is conducted using a power-law viscoplasticity model in the bulk material and fatigue damage evolution in the cohesive zone. This approach is characteristic of crack growth under cyclic loading in creep-ductile materials. The model is then calibrated to fatigue crack growth rates in Alloy 617.

The results of the parametric study demonstrate that low viscoplastic rate sensitivity is associated with crack growth retardation, while high rate sensitivity is associated with crack growth acceleration following OLs. At intermediate values of the rate sensitivity characteristic of many solid solution strengthened alloys, post-OL acceleration and retardation nearly cancel each other out. The equivalent viscoplastic strain fields shown in Fig. 1 indicate that this transition is strongly correlated with the magnitude of the viscoplastic strain near the location where the OL was applied. This trend is robust to variations in strain hardening and the cohesive zone damage parameters. The value of the rate sensitivity corresponding to the transition from retardation- to acceleration-dominated behavior depends on the frequency of the applied loading. The predicted post-OL crack growth for the calibrated model shows good agreement with trends observed in experiments.

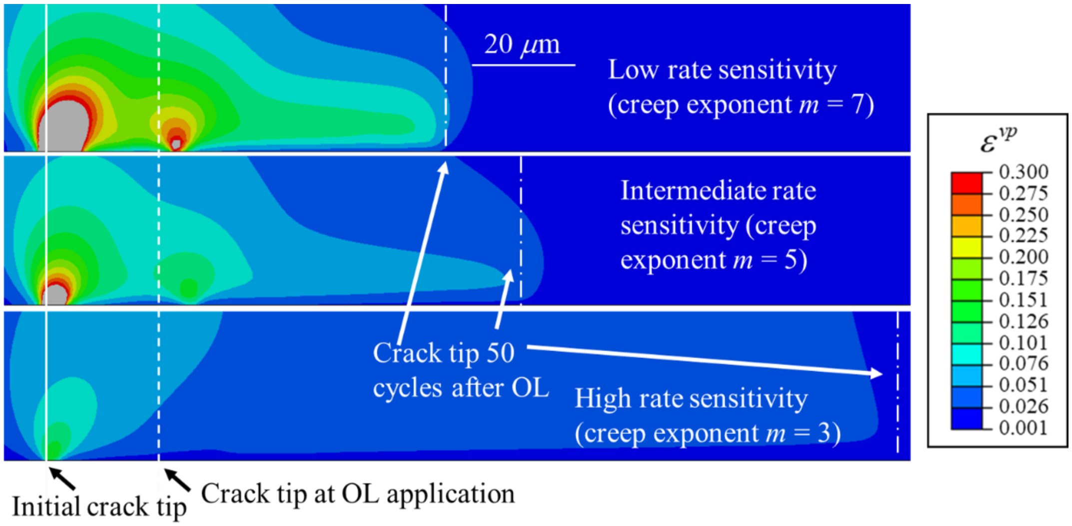

Fig. 1 – Equivalent viscoplastic strain contours for simulations with one OL and varied rate sensitivity.

Next, crack extension in Alloy 718 is studied using a Kocks-Mecking-based constitutive model in the bulk material and a stress- and time-dependent damage evolution equation in the cohesive zone. The Kocks-Mecking formulation accounts for hardening and dynamic recovery due to dislocation storage and annihilation mechanisms, respectively. The development of geometrically-necessary dislocations in regions with high viscoplastic strain gradients is also included in the constitutive formulation.

Calibration of the damage model in the cohesive zone demonstrates that crack growth rates under both sustained loading and constant-amplitude cyclic loading are captured using the stress- and time-dependent damage evolution. Subsequent simulations address crack growth following OLs applied during three different types of loading: cyclic loading, sustained loading, and a trapezoidal loading waveform. Crack growth retardation is predicted in all cases. The amount of retardation strongly depends on the OL ratio, in agreement with experiments in the literature. The retardation increases significantly above an overload ratio of 1.3, with crack arrest occurring in some cases with an overload ratio of 1.5. The computations also demonstrate that dynamic recovery enhances stress relaxation near the crack tip, leading to increased viscoplastic strain and crack growth retardation. On the other hand, hardening associated with geometrically necessary dislocations restricts crack-tip viscoplastic deformation and reduces post-OL retardation.

3. Conclusions

Finite element computational fracture mechanics simulations reveal that post-OL crack growth at elevated temperatures depends strongly on local viscoplastic strain near the crack tip. Changes in the characteristics of the crack-tip viscoplastic strain fields are associated with the transition from retardation- to acceleration-dominated post-OL crack growth. The crack-tip viscoplastic strain in turn depends strongly on the material rate sensitivity. Post-OL crack growth predictions agree with trends in experiments. The results thereby help explain the apparent contradictions for creep-ductile Alloy 617 and creep-brittle Alloy 718 in crack growth experiments containing OLs.

Acknowledgements

This research was supported by the U.S. Department of Energy, National Energy Technology Laboratory, under contract Number DE-FE0011796 and by the Office of Nuclear Energy, Nuclear Energy University Program under Award Number DE-NE0000722.