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Creep, plasticity, and fatigue of single crystal superalloy

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ABSTRACT

Single crystal components in gas turbine engines are subject to such extreme temperatures and stresses that life prediction becomes highly inaccurate resulting in components that can only be shown to meet their requirements through experience. Reliable life prediction methodologies are required both for design and life management. In order to address this issue we have developed a thermo-viscoplastic constitutive model for single crystal materials. Our incremental large strain formulation additively decomposes the inelastic strain rate into components along the octahedral and cubic slip planes. We have developed a crystallographic-based creep constitutive model able to predict sigmoidal creep behavior of Ni base superalloys. Inelastic shear rate along each slip system is expressed as a sum of a time dependent creep component and a rate independent plastic component. We develop a new robust, computationally efficient rate-independent crystal plasticity approach and combined it with creep flow rule calibrated for Ni-based superalloys. The transient variation of each of the inelastic components includes a back stress for kinematic hardening and latent hardening parameters to account for the stress evolution with inelastic strain as well as the evolution for dislocation densities. The complete formulation accurately predicts both monotonic and cyclic tests at different crystallographic orientations for constant and variable temperature conditions (low cycle fatigue (LCF) and thermo-mechanical fatigue (TMF) tests). Based on the test and modeling results we formulate a new life prediction criterion suitable for both LCF and TMF conditions.

1. Introduction

Failure is a localized process evolving in time and leading to global structure instabilities when a limiting state is met. This paper describes how the material properties and loading affects the damage initiation and propagation. High temperature superalloy material damage is most closely tied to crystallographic slip along definite crystallographic planes. Among micromechanical deformation mechanisms, slip along crystallographic planes controls the evolution of the microstructure in materials, and in turn, leads to failure. Energy dissipation in a loaded structure could take place either by plastic deformation or by microcracking. Under applied stress, slip bands run into each other, generating new dislocations and also forming a dislocation pile up next to an obstacle. This means that slip bands intersection may result in the appearance of cracks.

We studied the micromechanics of the high temperature creep, plasticity, and damage accumulation in single crystal nickel base superalloy. These alloys are used in turbine blade and vane applications in advanced commercial and military gas turbines and in the turbopumps for the space shuttle main engines. Significant progress in airfoil design led to development of thin hollow air-cooled and film-cooled blades reducing the alloy temperature. However, this process causes high temperature gradients in the blade making local creep and thermo-mechanical fatigue (TMF) a problem that is crucial in the proper blade damage tolerant design (Cowles, 1996). The final objective of such a study should be the development of a robust predictive tool to relate single crystal structure macroscopic behavior and fracture crack initiation to micromechanical events (Rubeša, 1996). Modern blade design still relies mostly on empirical approaches, because the nonlinear cyclic visco-plastic structural analysis for single crystal blades requires advanced material constitutive and damage evolution models that still have not reached maturity and are computationally expensive. Historically, only secondary creep effects were considered (e.g., Larson–Miller, etc.) in engineering calculations. However, during thermo-mechanical loading of high temperature single crystal turbine parts, all three creep stages: primary, secondary and tertiary, manifest themselves and none of them can be neglected (Epishin and Link (2004); Staroselsky and Cassenti (2006)). Account must be taken of all creep mechanisms, and is especially important in the case of non-homogeneous thermal loading of components with

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