MESO APPROACHES FOR THE CREEP DAMAGE BEHAVIOR OF NICKEL-BASE DIRECTIONALLY SOLIDIFIED SUPERALLOYS

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Abstract: A self-consistent creep damage constitutive model and a finite element model have been developed for nickel-base directionally solidified superalloys. Grain degradation and grain boundary voiding are considered. The model parameters are determined from the creep test data of a single crystal and a directionally solidified superalloy with a special crystallographic orientation. The numerical analysis shows that the modeled creep damage behaviors of nickel-base directionally solidified superalloys with different crystallographic orientations are in good agreement with the experimental data.

Key words: directionally solidified superalloy; creep meso damage; finite element model; self-consistent model

Introduction

Nickel-base high temperature resistance superalloys are widely used in gas turbines and jet engines. Directionally solidification was introduced to enhance creep strength by eliminating grain boundaries normal to the applied stress where voids are likely to occur under creep load. In practice, however, the applied stress may not be uniaxial nor directed parallel to the grain boundaries. Single crystals were thus developed. Congregation of low temperature melting elements on grain boundaries, grain boundary oxidation, etc., are additional factors that would degrade the creep property and hence prompted the development of directionally solidified superalloys.

Real directionally solidified superalloys consist of large numbers of grains with one common and two random crystallographic orientations. Direct modeling of the superalloys with real number and configuration of grains is currently infeasible[1]. Finite element model and self-consistent model are two basic approaches. When the superalloys are subjected to a constant, prescribed traction giving rise to a uniform, its overall creep strain is generally calculated from the average strains of its constituent grains, assuming that the grain boundary sliding effects can be neglected for the kind of superalloys. The creep strain in each grain in turn is contributed by the slip strains of its individual slip systems. Apparently, the material degradation is supposed to initiate in the slip systems and grain boundary voiding is initiated simultaneously.

The goal of the paper is to predict the creep damage behavior of nickel-base directionally so
The Creep Damage Behavior of Nickel-Base Stabilized Superalloys in different crystallographic orientations with two approaches. In order to quantitatively test such models, it is necessary to run tests on both the single crystal (SC) and the directionally solidified superalloy (DS) versions of the same alloy and ensure that the single crystal samples have properties that closely match those of the single crystal grains in the polycrystal sample, i.e., directionally solidified superalloy. In this investigation, single crystal sample has the same chemical composition with that of the DS superalloy. The grains in the DS superalloy and SC sample consist of two phases, γ and γ', and the volume fraction of γ' phase in the samples is 62% and 65%, respectively.

1 Models

1.1 Finite element model

The present model simulates the superalloys by a small number of grains and accounts for the individual interactions that would involve the nonuniformity of load stress and strain. A finite element method is used to account for grain boundary void growth and material degradation. A block of \( n \times n \times n \) elements with same cubic size is used. The number of grain is \( n \times n \). The finite element boundary is that the creep stress loads on two opposite faces and the rest faces are free. The finite element program developed in Ref. [2] is adopted, in which the effect of finite deformation is considered.

1.2 Self-consistent model

Localization of the macroscopic stress tensor \( S \) (external applied stress) in the grain can be realized for the time-dependent creep behavior by a self-consistent method to obtain the granular stress tensor \( \sigma \). In this study, the following relation is used in the increasement form\(^3\)

\[
d\sigma_i^i(t) = -2\mu(1-\beta)e^{-\beta t}(d\varepsilon_i^i - d\varepsilon_i^e),
\]

\[
\sigma_{kk} = S_{kk},
\]

where \( \sigma_{kk} \) and \( \sigma_i^i \) are the hydrostatic and deviatoric parts respectively, \( \mu \) is the shear modulus, \( \beta = 2(4 - \nu)/15(1 - \nu) \) (\( \nu \) is the Poisson ratio), \( T = \mu/\eta \) (\( \eta \) is the shear viscosity), such that \( S_i^i = 2\eta\varepsilon_i^e \), \( e_i^e \) is the creep strains of the grains, \( e_i^e \) is the macroscopic strains, \( t \) is the creep time. The above relation represents and equation in a non-damaged medium. For the sake of simplicity, it is supposed that this relation is still valid for the damaged medium.

In the calculation, all the grains have one common and two random crystallographic orientations. The macroscopic coordinate is relative to the applied stress such that \( S = (0,0,S_{33},0,0,0) \). The meso coordinate is relative to the crystallographic coordinate. A transformation from the meso coordinate to the macro one is used.

1.3 Crystallographic constitutive

The same crystallographic constitutive is applied in the two models.

The resolved shear stress \( \tau^{(a)} \) on a slip system \( (a) \) can be related to the granular stress \( \sigma_i^i \) on the grain as

\[
\tau^{(a)} = V_q \sigma_i^i,
\]

in which \( V_q \) can be expressed in terms of the slip direction \( b_i \) and slip plan normal \( a_i \) of the slip system \( (a) \) under consideration

\[
V_q = \frac{1}{2}(b_i a_j + b_j a_i).
\]