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A microstructure-sensitive constitutive modeling of the inelastic behavior of single crystal nickel-based superalloys at very high temperature

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ABSTRACT

The prediction of the viscoplastic behavior of nickel-based single crystal superalloys remains a challenging issue due to the complex loadings encountered in aeronautical engine components such as high pressure turbine blades. Under particular in-service conditions, these materials may experience temperature cycles which promote the dissolution of the strengthening γ' phase of the material on (over)heating, and subsequent precipitation on cooling, leading to a transient viscoplastic behavior.

Within this context, a model was recently developed by Cormier and Cailletaud (2010) to fulfill the effects of fast microstructure evolutions occurring upon high temperature non-isothermal loadings. New internal variables were introduced in the crystal plasticity framework to take into account microstructure evolutions such as γ' dissolution/precipitation and dislocation recovery processes which are known to control the creep behavior and life. Nevertheless, this model did not consider the γ' directional coarsening, one of the main microstructural evolutions occurring specifically at high temperature. In addition, no kinematic hardening was considered to describe the mechanical behavior, leading to a poor description of cyclic loadings.

This paper details the development of a new model by introducing new internal variables for both modeling the γ' directional coarsening and the evolutions of isotropic and kinematic hardening under complex loading paths.

This model was calibrated using monotonous and cyclic experiments performed on [001] oriented single-crystal samples and both under isothermal and non-isothermal conditions. Thereby, it is able to predict microstructural evolutions for complex thermal and mechanical loadings as well as internal stress evolutions whatever the thermomechanical history. The model efficiency was highlighted by comparing FEM simulation and experimental results of a non-isothermal creep test on a notched sample (i.e. under complex mechanical stress state).

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Nomenclature

$\underline{\underline{\sigma}}_{eff}$	effective stress tensor
$\underline{\underline{m}}^s$	orientation tensor
$\underline{n}^s$	normal to the slip system plane
$\underline{l}^s$	slip direction in the slip plane
γ^s	viscoplastic shear on slip system s
$\underline{\underline{\varepsilon}}_p$	viscoplastic strain tensor
$\underline{\underline{\sigma}}$	stress tensor
v	accumulated viscoplastic strain
v^s	accumulated viscoplastic strain on the slip system s
f_{eq}	volume fraction of the γ' phase at thermodynamic equilibrium
f_s	small γ' precipitates volume fraction
f_l	large γ' precipitates volume fraction
$\dot{T}$	heating/cooling rate
τ^s	resolved shear stress on slip system s
r^s	isotropic hardening on the slip system s
τ_0^s	critical resolved shear stress on the slip system s
h_{sj}	components of the hardening matrix
ρ^s	isotropic state variable on slip system s
Q	dislocation hardening
τ_{Orowan}	Orowan stress
w_{001}	γ channel width along the [001] direction
G	shear modulus (=C_{44} in the present case)
B	Burgers vecteur magnitude
$f_{thermic}$	contribution of the thermal loading leading to w_{001} evolution
$f_{mechanic}$	contribution of the mechanical loading leading to w_{001} evolution
$f_{isotropic}$	contribution of the thermal holding leading to w_{001} evolution
$f_{diffusion}$	contribution of the diffusion process leading to w_{001} evolution
$\tau_{diffusion}$	characteristic time of diffusion
ξ	strain rate sensitivity of the γ' rafting
x^s	kinematic hardening on the slip system s
α^s	kinematic variable on the slip system s
a^*	temperature dependent recovery variable
D_c	damage scalar
$\Delta\varepsilon_p$	plastic strain amplitude
$\Delta\sigma$	stress amplitude

1. Introduction

Monocrystalline nickel base superalloys are widely used in the hottest parts of aeroengines or industrial gas turbines (Caron and Khan, 1983). Blades made of these alloys operate for thousands of hours at temperatures as high as 1100 °C (Reed, 2006). These alloys are chosen for their superior mechanical performances at high temperatures, in particular their creep resistance for uncooled components such as high pressure turbine blades of turboshaft engines for helicopters or small industrial gas turbines. These interesting properties result from the precipitation of a high volume fraction (close to 70%) of the long-range ordered $L1_2$ γ' phase which appears as cubes coherently embedded in a face-centered cubic (fcc) solid solution γ matrix.

Furthermore, a single crystal superalloy with a negative (respectively positive) γ/γ' lattice mismatch (coherency stress due to the difference between the lattice parameters of the γ and γ' phases) exhibits a directional coarsening of the γ' precipitates perpendicularly (respectively parallel) to the applied tensile stress axis (N-type coarsening, respectively P-type coarsening). This morphological evolution, often known under the "γ' rafting" denomination, usually takes place during the high temperature ($T > 800$ °C) primary creep stage when the γ' phase has entirely coalesced and the γ channels have become wider along the applied stress axis (Henderson et al., 1999; Shui et al., 2006). Moreover, during severe thermomechanical histories, thermal loadings can also induce microstructural changes, especially fast ones such as γ' dissolution. These changes modify the internal stress state, as le Graverend et al. (2012)) have already shown by X-ray synchrotron study for temperature peaks representative of helicopter in-operation emergency ratings (Cormier et al., 2007b, 2008; le Graverend et al., 2010). Under such circumstances, the material's microstructure is out of equilibrium, so that the properties for a given temperature differ from the steady state (Cailletaud, 1979; Cormier et al., 2008; le Graverend et al., 2010).

The recent development of microstructure-sensitive models (i.e. models in which internal variables representing microstructure are added) (Cormier and Cailletaud, 2010; Fedelich et al., 2012; Khan and Liu, 2012; Shenoy et al., 2008; Zhu et al.,