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Intergranular mechanical behavior in a blade groove-like component by crystal plasticity model with cohesive zone model

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ABSTRACT

Creep-induced intergranular mechanical behavior was investigated in the first blade groove-like component on a steam turbine rotor. The involved method combined the crystal plasticity constitutive model with the cohesive zone model, to describe the stress-strain behavior inside the material's grains and to model the traction-separation responses at the grain boundaries, respectively. Three displacement-drive FE submodels of the blade groove-like component were established to explore the effects of cohesive elements and predefined initial cracks. It was found that the cohesive elements relieved the stress concentration and eased the effects of material heterogeneity among the grains. With predefined initial cracks, the grain boundaries around the fillet surface were more greatly deformed to satisfy the overall displacement compatibility. The grain boundaries far inside of the blade groove, however, were extruded due to the bending behavior of the blade groove. Analysis of the overall intergranular mechanical behavior confirmed the long-term inhibitory effect of the initial cracks on further cracking.

1. Introduction

Because the blade grooves of steam turbine rotors operate under high-temperature conditions and are subject to strong blade tensile force, they are always vulnerable to stress concentration. The creep behavior during long-term operation can lead to material degradation and premature failure due to intergranular fractures. In our previous studies, which were based on macroscopic constitutive material models [1,2], the first blade groove (shown in the largest magnified view of Fig. 1) on a steam turbine rotor was found to be the most easily damaged (Fig. 1), as has been noted in previous studies [3,4]. Damage-based macroscopic constitutive material models are widely used in the structural design, due to their computational efficiency. However, a large material test database is necessary for the accurate prediction of structural strength. Damage on the macrostructural scale for the description of material failure is always established on the basis of empirical equations, but it is unable to disclose the cracking mechanism on a microscopic scale. Intergranular crack initiation or propagation results in a damage-related reduction of the load-bearing area. Moreover, damage on the microstructural scale is already great once the macrostructural damage can be detected. Thus, understanding intergranular mechanical behavior and the process of early crack initiation under creep loading conditions is of particular importance for strength assessment and prediction of the residual lifetimes of blade groove-like components. Such understanding is also necessary to optimize and correct the macroscopic damage variable.

Abbreviations: BCC, body-centered cubic; CE, cohesive element; CPCM, crystal plasticity constitutive model; CZM, cohesive zone model; GB, grain boundary; QUADSCR, quadratic nominal stress damage-initialization index; SDEG, stiffness degradation; UMAT, user-defined material subroutine

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Nomenclature

C_{11}	anisotropic elastic modulus
C_{12}	anisotropic elastic modulus
C_{44}	anisotropic elastic modulus
$D(\delta)$	damage variable
E_{coh}	cohesive energy
E_{el}	specific elastic energy
E_{pl}	specific plastic (fracture) energy
$g^{(\alpha)}$	isotropic hardening variable
h_0	initial hardening modulus
$h_{\alpha\beta}$	hardening moduli
K_{nn}	normal grain boundary stiffness
K_{ss}	shear grain boundary stiffness
K_{tt}	shear grain boundary stiffness
q	material hardening constant
T_0	constitutive thickness of the cohesive element
t	time
t_n	normal traction of the cohesive element
t_s	shear traction of the cohesive element
t_t	shear traction of the cohesive element
t_n^0	maximum normal traction of the cohesive element
t_s^0	maximum shear traction of the cohesive element
t_t^0	maximum shear traction of the cohesive element
ε_n	normal strain of the cohesive element
ε_n^0	damage-initialization strain
ε_s	shear strain of the cohesive element
ε_t	shear strain of the cohesive element
θ	misorientation angle
σ	average von Mises stress
$\Delta\sigma$	average stress difference
δ	opening displacement
δ_n^0	damage-initialization opening displacement
δ_n^f	maximum separation opening displacement
δ_n	normal opening displacement
δ_s	shear opening displacement
δ_t	shear opening displacement
τ_s	stage one shear stress
τ_0	yield shear stress
$\tau^{(\alpha)}$	resolved shear stress of slip system α
γ	cumulative shear strain on all slip systems
$\dot{\gamma}^{(\alpha)}$	resolved slip rate of slip system α
$\dot{\gamma}_0^{(\alpha)}$	reference slip rate of slip system α
ν	Poisson's ratio

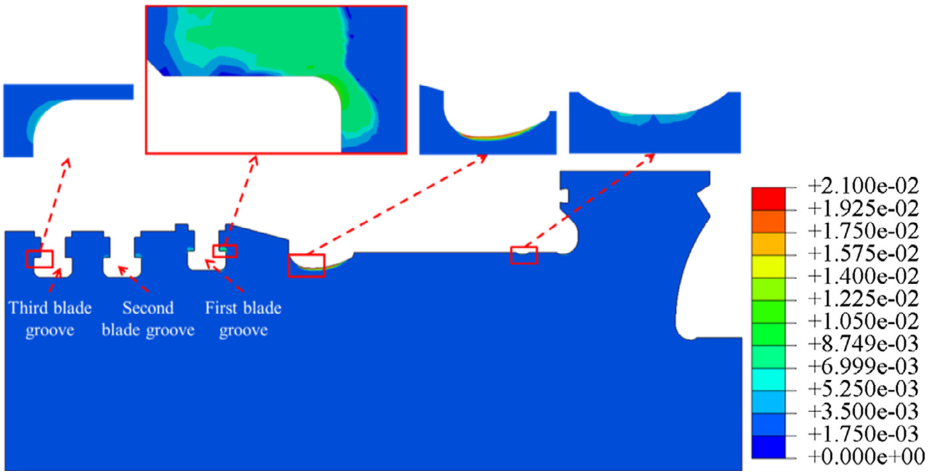

Fig. 1. Distribution of creep-fatigue damage and the critical regions on the rotor [1].

Numerous efforts have been made to investigate the mechanical behavior of polycrystalline alloys and components under creep loading conditions through the use of crystal plasticity theory [5–10]. However, most studies have been overly simplified by focusing only on the stress-strain behavior inside the grains, without considering the grain boundaries (GBs) and their mechanical behavior. This oversimplification has probably resulted from the lack of appropriate mechanical models and numerical methods. However, the differences among the crystallographic orientations of grains actually lead to differing mechanical responses and variable increases in stress at the GBs. These material discontinuities are often the sources of damage and cracking in polycrystalline materials, especially under creep loading conditions. Among the existing numerical methods, the cohesive zone model (CZM) has been shown to be a convenient and effective means to explicitly account for GBs and to predict intergranular crack initiation and evolution [11–16]. Therefore, this study implements the crystal plasticity constitutive model (CPCM), coupled with the CZM in the ABAQUS FE code. The CPCM is used to describe the mechanical behavior of the grains' interiors, taking account of their crystallographic orientations and slip systems. Meanwhile, the CZM is embedded into the zero-thickness cohesive elements (CEs) and is used to simulate the traction-separation relationship at the GBs.

The coupling of CPCM and CZM methods has been used to study mechanical behavior in fracture specimens and structures. Paggi et al. [17] investigated the interplay between cohesive cracking and plasticity in polycrystals. They found that the results from this method showed good agreement with the results from uniaxial tensile experiments. Kebriaei et al. [18] used the method for realistic modeling of bonding and debonding between two kinds of alloys. The ability of this method to describe interface behavior was

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