Modeling Intergranular Damage Assisted by Oxidation in Nickel-Based Superalloys

Ayoub El-Habyb*†1, Samuel Forest[1], Jean-Michel Scherer[1], Ammar Kais[1], Florent Coudon[2], and Louis Augustins[2]

[1]Mines Paris - PSL (École nationale supérieure des mines de Paris) – Centre des Matériaux (CMAT), CNRS UMR 7633, BP 87 F-91003 Evry Cedex – France

[2]Safran Tech – Safran Tech, Rue des Jeunes Bois, Châteaufort, CS 80112, 78772 Magny-Les-Hameaux, FRANCE – France

Abstract

Nickel-based superalloys, such as the DS200+Hf, are extensively used in high-temperature components of aerospace turbines, particularly for low-pressure turbine blades in CFM-56 and LEAP engines (1). These alloys generally feature a columnar grain structure with the main grain axis closely aligned with the principal loading direction (e.g., centrifugal forces in rotating components). Furthermore, the directional solidification process ensures that the main grain axis is typically near a (001) crystallographic orientation.
This study focuses on modeling the mechanisms of intergranular damage in the directionally solidified DS200 + Hf superalloy, considering local phenomena such as cracks, microcavities, and oxidation, which critically influence the initiation and propagation of intergranular cracks. The damage evolution was examined using finite element simulations and experimental data (2), with the microstructural characteristics, including grain size and texture, determined through electron backscatter diffraction (EBSD) analyses.

To capture these complex phenomena, a novel phase-field method for fracture modeling in polycrystalline materials was developed. Numerous studies have addressed this issue by incorporating cohesive models at grain boundaries (3, 4). However, these models often face convergence challenges, particularly in complex surface geometries. Musienko et al. (5) proposed an alternative approach, defining grain boundaries through a viscoplastic model with damage, implemented using a specifically designed mesh to represent grain boundaries with a finite thickness. While this model demonstrates good convergence, it introduces a sharp transition in behavior between the grains and the grain boundaries. To address these limitations, the phase-field model offers a versatile framework with an internal length scale tailored for systems with sharp interfaces. Nguyen et al. (6, 7) proposed a phase-field approach for polycrystalline materials, where interface failure is governed by a cohesive law embedded within a regularized variational framework. The interfaces in their model are captured using a level-set method.

The present study focuses on developing a model that excludes the influence of oxidation. This model is built on the finite strain framework and integrated into the Méric-Cailletaud model, employing a two-potential approach for low strain rates and high strain rates to

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[*] Speaker

[†] Corresponding author: ayoub.el-habyb@minesparis.psl.eu

capture crystalline viscoplasticity at the grain level. The model is enhanced with a static phase-field method, enabling the distinction between grain boundaries and grains through a diffuse interface representation. Additionally, a Lemaitre-type damage law is incorporated to describe the evolution of damage, including deformation mechanisms induced by damage. This model is implemented in the finite element code Z-set, with both explicit and implicit resolution.

The model was validated through simulations of creep and tensile tests, with results compared to experimental data obtained under vacuum conditions. The findings highlight the model's ability to replicate the nucleation and propagation of intergranular cracks, offering valuable insights into the damage mechanisms of directionally solidified superalloys.

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