Micro-mechanical Modelling of Single Crystal Nickel-base Superalloys

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Introduction

Single crystal nickel-based superalloys are widely used as gas turbine blade materials because of their superior high temperature behaviour. The excellent properties are attributed to the two-phase composite microstructure consisting of a γ matrix containing a large volume fraction of γ' precipitates (Figure 1a).

The ability to perform a reliable life assessment is crucial for both gas turbine component design and maintenance. Since the microstructure morphology may change during operation (Figure 1b), a micro-mechanical model was developed to simulate the superalloy mechanical response.

Multi-scale approach

A multi-scale approach is followed to bridge the gap in length scales between the engineering level and microstructural level, see Figure 2b.

Constitutive behaviour

A strain-gradient crystal plasticity model is used to model the matrix phase constitutive behaviour:

\[
\dot{\epsilon}^m = \gamma_0 \left( \frac{\tau_{\text{eff}}}{S^c} \right)^m \left[ 1 - \exp\left( -\frac{S^c}{\tau_{\text{eff}}} \right) \right] \cdot \text{sign} \left( \frac{\tau_{\text{eff}}}{\tau_{\text{eff}}^c} \right)
\]

A similar relation is used for the precipitate phase, describing two precipitate deformation mechanisms:

\[
\dot{\epsilon}^p = A \rho_{\text{GND, min}}^p \dot{\gamma}_{\text{slip}} \cdot \text{shearing} + B \rho_{\text{GND, min}}^c \dot{\gamma}_{\text{climb}} \cdot \text{climb}
\]

\( \tau_{\text{eff}} \) - combination of applied stress, lattice misfit stress and dislocation induced back stress
\( S^c \) - slip resistance (~ dislocation density)
\( \tau_{\text{eff}}^c \) - Orowan threshold stress (~ particle spacing)
\( \rho_{\text{GND, min}} \) - interface dislocation density

Results

Model parameters were determined for alloy CMSX-4 and material behaviour was predicted (Figure 3,4).

Figure 1 As received and degraded superalloy microstructure.

Figure 2 a) Microstructural unit cell b) Multi-scale approach.

Figure 3 CMSX-4 macro stress-strain curves and micro-results.

Figure 4 Turbine blade temperature, stress and calculated creep strain distribution for a fine and a coarse microstructure.