Micro-mechanical modelling of single crystal nickel-nase superalloys

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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).

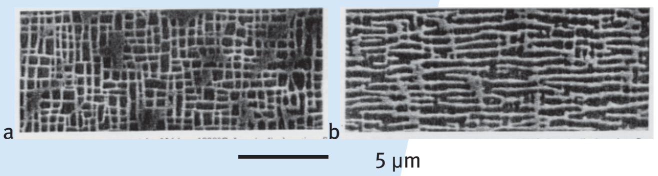


Figure 1 *As received and degraded superalloy microstructure.*

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.

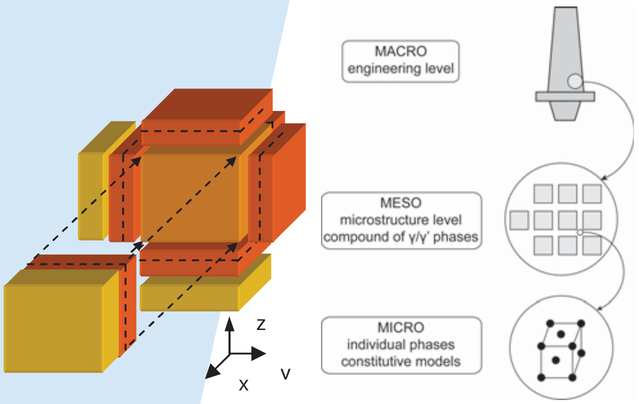


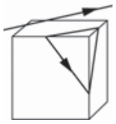
Figure 2 *a) Microstructural unit cell b) Multi-scale approach.*

On the engineering level a Finite Element method is adopted and a microstructural unit cell (Figure 2a) is used to calculate the averaged response for each material point. The unit cell contains 1 precipitate, 3 matrix and 6 double interface regions.

Constitutive behaviour

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

$$\dot{\gamma}^{\alpha} = \dot{\gamma}_0 \left\{ \frac{\left|\tau_{eff}^{\alpha}\right|}{s^{\alpha}} \right\}^{m} \left\{ 1 - \exp\left[-\left(\frac{\left|\tau_{eff}^{\alpha}\right|}{\tau^{or}} \right)^{n} \right] \right\} \operatorname{sign}\left(\tau_{eff}^{\alpha}\right) \Rightarrow$$



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

$$\dot{\gamma}^{\alpha} = A\rho_{GND,\min}^{\alpha} f_{diss} \left\{ 1 - \exp\left(-\frac{\left|\tau_{eff}^{\alpha}\right|}{s_0^{\alpha}} \right) \right\}^{p} \quad \textit{shearing} \Rightarrow$$

+

$$+ B\rho_{GND,\min}^{\alpha} v_{\text{climb}}^{\alpha} \left\{ 1 - \exp\left(-\frac{\left|\tau_{eff}^{\alpha}\right|}{\tau_{cr}^{\alpha}} \right) \right\} \quad \textit{climb} \Rightarrow$$

τ_{eff} - *combination of applied stress, lattice misfit stress and dislocation induced back stress*
s^{α} - *slip resistance (~ dislocation density)*
τ^{or} - *Orowan threshold stress (~ particle spacing)*
τ_{cr} - *threshold stress for climb*
$\rho_{GND,min}$ - *interface dislocation density*

Results

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

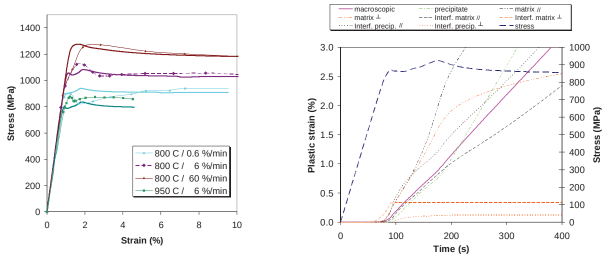


Figure 3 *CMSX-4 macro stress-strain curves and micro-results.*

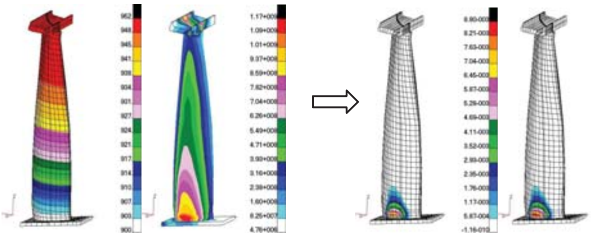


Figure 4 *Turbine blade temperature, stress and calculated creep strain distribution for a fine and a coarse microstructure.*