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Full-field Modeling of the Zener Pinning Phenomenon in a Level Set Framework - Discussion of Classical Limiting Mean Grain Size Equation

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Context

Pinning of grain boundaries by second phase particles is widely used to control the grain size during forming process of superalloys.

Classical Zener pinning law predicting the limiting mean grain size [1]:

$$\langle R_f \rangle = K \frac{r_p}{f_{gb}}$$

where \(\langle R_f \rangle\) is the mean grain size, \(r_p\) is the mean particle radius, and \(f_{gb}\) is the volume fraction of particles. \(K\), a parameter depending on the assumptions.

Relation to the volume fraction of particles located at grain boundaries \(f_{gb}\) [2]:

$$\langle R_f \rangle = K \frac{r_p}{f_{gb}}$$

Numerical model

Level Set Framework:

- Adaptive metric based meshing remeshing tool [4] was used.
- New direct and parallel reinitialization algorithm [5] was incorporated.

Boundary condition at precipitate/matrix interface:

$$\nabla \psi = \nabla \psi \cdot \hat{n} = \sin(\alpha)$$

Simulation parameters:

Material: Inconel 718

\(M = 2.3 \times 10^{-23} \text{m}^3/(\text{J}s)\)

\(\gamma = 0.6 \text{J/m}^2\)

\(\alpha = 0^\circ\) (incoherent precipitates)

Particle radii: 0.2, 0.4, 0.6, 0.8 \(\mu\text{m}\)

Area fraction: 1-8%

Domain size: 0.3 \(\times \text{0.3} \text{ mm}^2\)

Number of grains: 2600

Initial mean grain size: \(<R_0> = 3.35 \mu\text{m}\)

Time step: 0.1 s

16 CPUs (Xeon 1.2 GHz)

(computation time: 1-2 days)

2D simulation results for grain growth:

New mean field model for the limiting mean grain size

\(f_{gb}\) and \(<R_f>\) are measured at the steady state (when \(<R_f>\) becomes stable)

1) The radius of precipitates (for a given \(f\)) affects drastically the grain growth kinetics

2) \(K\) and \(m\) were found to depend on \(r_p/<R_0>\) (see figures for \(K\) and \(m\))

Expression obtained for the limiting grain size:

$$\langle R_f \rangle = 0.362<\langle R_0 \rangle f_{gb}^{-0.853(r_p/<R_0>)^{0.428}}$$

Current work

References