A Level Set Finite Element Anisotropic Grain Growth Study
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## Thermodynamics

The turbines of aircraft engines, obtained by hot forging, must withstand extreme pressures at extreme temperatures and resist to fatigue crack propagation.

If \( \gamma \) is the grain boundary energy and \( P_{\text{B}} \) is the pressure felt by the grain boundary. At equilibrium, neglecting the torque terms:

\[
P_{\text{B}} = -\gamma \kappa
\]

where \( \kappa \) is the curvature of the grain boundary \([\text{Her}99]\). The velocity of the grain boundary \( \beta \) is defined as:

\[
\beta = \mu P_{\text{B}}
\]

where \( \mu \) is the mobility of the grain boundary and \( \beta \) is the unitary normal to the boundary.

## Anisotropic Adaptation

A supplemental convection term due to the weak formulation is taken into account in the anisotropic model using a Convection-Diffusion assembly of the FE matrix. Equation (4) becomes

\[
\frac{\partial \varphi}{\partial t} + \frac{\partial}{\partial r} (\varphi v_r) + \frac{\partial}{\partial \theta} (\varphi v_\theta) = 0
\]

using a FE solver.

## Material

The material of choice for these disks are often Ni based superalloys whose compositions and microstructures have to be optimized. Annealing twins, boundaries of lower energy, are often present in these microstructures and play an important role in the in-service properties \([\text{TICV}16]\).

## LS-FE

The boundary network \( \Gamma \) is represented by a set of \( N \) signed distance functions such that for \( (X, t) \in \Omega \times [0, t_{\text{end}}) \):

\[
\{ \phi_i(X, t) \mid \exists x \in \Omega, \| \nabla \phi_i \| = 1 \} \quad \forall i \in \{0, \ldots, N\}
\]

In order to resolve the grain growth problem, a transport equation is used:

\[
\frac{\partial \varphi}{\partial t} + \frac{\partial}{\partial r} (\varphi v_r) + \frac{\partial}{\partial \theta} (\varphi v_\theta) = 0
\]

## Sensitivity

- \( \Delta m \) is the change in mass.

\[
\Delta m = \frac{\partial m}{\partial t} = \frac{\partial}{\partial t} (\rho v r) = \frac{\partial}{\partial t} (\rho v \theta)
\]

## Varying Anisotropy

### Equilibrium Angles

- As \( r \) increases, the solutions are closer and closer together.
- The angles for \( r \neq 1 \) are clearly much lower than predicted by the theory.
- Equation (9)/Young’s equilibrium is not respected.
- Although convergence of the method is ensured, the simulation does not arrive at the correct solution.
- The question must be revisited in the state of the art.

### Velocities

- Relative velocities of the triple junction get lower as \( r \) increases.
- A stationary state is obtained \((v_\theta = \text{const})\) for \( t = 0.14 \).
- Kinetics are around twice as fast as they should be for \( r = 2 \).
- Obtained velocities at the triple junction are much higher than those predicted using the imposed grain boundary energies for every \( r \).
- Kinetics of the triple junction are coherent with obtained angles.
- Kinetics of the profile completely dependent on the equilibrium angles.

## Conclusions

- The equilibrium angles at the triple junction cannot be obtained naturally without considering torque terms.
- The kinetics of the triple junction and its surroundings are completely dependent upon the equilibrium angles.

### Bibliography


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