An Enthalpy-Based Finite Cell Method for the Simulation of the Phase Change in Additive Manufacturing

★★★★★	Programming skills (JAVA)	Start:	immediately
★★★★☆	Finite Element Method	Duration:	6 months
★★★☆☆	Development	Language:	English/German
★★★★★	Research		

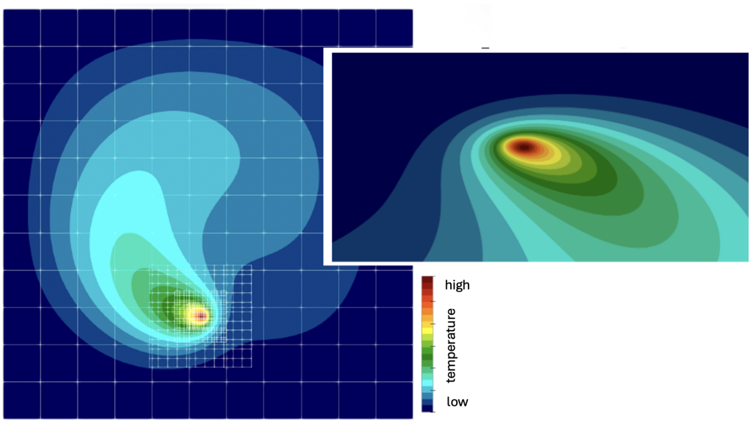

Abbildung 1: Qualitative temperature field from Laser Powder Bed Fusion

Motivation

In Laser Powder Bed Fusion (LPBF), a representative technology of modern additive manufacturing, the melt pool constitutes the birthplace of the part's microstructure and a primary source of process-induced defects. Accurate numerical simulation of the melt pool using the classical Finite Element Method (FEM) requires either an extremely fine mesh throughout the computational domain or a dynamically adaptive mesh that follows the moving laser source. Both approaches are computationally demanding and difficult to realize in practice, particularly for complex geometries characteristic of LPBF builds.

The *Finite Cell Method (FCM)*, a high-order fictitious domain approach, offers a viable alternative by overcoming key limitations of conventional FEM. Through a novel *unfitted overlay-refinement* strategy, FCM enables the resolution of sharp gradients and discontinuities in the solution field independently of the underlying discretization grid. In combination with a pseudo-liquid approach, the solid–liquid phase transition is modeled via a nonlinear variation of temperature-dependent material properties (e.g., enthalpy and thermal conductivity) within fixed cells. This formulation eliminates the need for an explicit fluid-flow description based on the Navier–Stokes equations, while still capturing the essential thermal signature of the LPBF process.

In this project, an existing FCM-framework is extended to an enthalpy-based simulation platform capable to approximate the local phase-change of the melt pool of a laser fusion printing method.

Literature, e.g.

[1] Datsiou, K.C., Ashcroft, I. Numerical investigation of laser powder bed fusion of glass. *Glass Struct Eng 9, 185–200* (2024)

[2] Kaess, M., Werz, M., Weihe, S. Residual Stress Formation Mechanisms in Laser Powder Bed Fusion – A Numerical Evaluation. *Materials 16(6):2321* (2023)

The project involves several extensions of the existing Java-based FCM framework to enable the simulation of additive manufacturing processes:

- Non-linear Thermal Solver: Extension of the stationary heat solver to handle temperature-dependent conductivity $\lambda(T)$ and implementation of the *Apparent Heat Capacity Method*. This method regularizes the enthalpy jump at the melting point by 'smearing' the latent heat L over a regularization interval ΔT:

  $$C_{app}(T) = C_p + L \cdot \frac{d\alpha}{dT}$$

  where $\alpha \in [0,1]$ denotes the liquid fraction, C_p the specific heat capacity and C_{app} the resulting apparent heat capacity.

- Pseudo-Liquid Modeling: In the liquid phase $(T > T_{melt})$, the thermal conductivity is artificially scaled (factor 3–5) to approximate convective heat transport (Marangoni effect). A *composed Gauss integration* (sub-cell integration) is employed to accurately capture the material properties within cells intersected by the phase boundary.

- Moving Heat Source & Refinement: Implementation of a moving Gaussian surface heat source for 'pseudo-stationary' analysis. To resolve the high thermal gradients in the *mushy zone* and the melt pool, a local unfitted overlay refinement (multi-level hp-refinement or sub-grid) is utilized.

- Verification: Validation of the implementation against the analytical *Rosenthal solution* for moving point sources to assess the accuracy of the FCM approximation.

- Prepare and typeset a scientific thesis which carefully documents your project using LaTeX.

Kontakt

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