On thermomechanical finite element based modelling of additive manufacturing processes of metals

Andreas Menzel

Institute of Mechanics, TU Dortmund University, Dortmund, Germany (www.iofm.de)
Division of Solid Mechanics, Lund University, Lund, Sweden (www.solid.lth.se)

Two different thermo-mechanically fully coupled finite element frameworks are briefly introduced in the context of the simulation of additive manufacturing processes, namely the so-called Particle Finite Element Method, [1], and an element activation framework, [2], which can also be combined with commercial finite element software such as Abaqus.

The latter approach is further specified towards the multi-scale modelling of laser powder bed fusion processes, focusing on thermo-mechanically coupled material response and an efficient simulation framework. Phase transformations are explicitly taken into account to predict microstructure evolution, residual stresses, and deformation, respectively distortion. Specifically, an efficient mutli-scale modelling framework (without full scale separation) for Powder Bed Fusion-Laser Beam / Metals (PBF-LB/M) is discussed. The model describes the respective material states – powder, melt and solid – while incorporating phase transitions between these. Physical phenomena, such as transformation-induced strains together with mass conservation, are included to naturally capture layer thickness reductions during phase transitions. For the scan island, a simplified material model is used to extract micro-mechanically motivated inherent strains. These strains enable efficient simulation-based prediction of residual stresses and resulting deformation in the final part, distinguishing this method from empirical averaging approaches. The framework also supports the incorporation of more advanced solid-state phase transformation models tailored for multiphase alloys, such as Ti6Al4V, as elaborated in [3]. Unlike empirical approaches, such as Johnson-Mehl-Avrami-Kolmogorov models or Koistinen-Marburger models, the proposed framework relies on related energy densities and physics-based evolution equations. To be specific, phase evolution is governed by dissipation functions, with coefficients determined by parameter identification using (limited) experimental data or Continuous Cooling Transformation (CCT) diagrams. This enables accurate numerical reproduction of CCT diagrams and reliable predictions of microstructure evolution, strains, and stresses.

[1] M. Schewe, I. Noll, T. Bartel, and A. Menzel. Towards the simulation of metal deposition with the Particle Finite Element Method and a phase transformation model. Comput. Methods Appl. Mech. Engrg., 437:117730, 2025. doi:10.1016/j.cma.2025.117730

[2] I. Noll, L. Koppka, T. Bartel, and A. Menzel. A micromechanically motivated multiscale approach for residual distortion in laser powder bed fusion processes. Additive Manufacturing, 60(Part B):103277, 2022. doi:10.1016/j.addma.2022.103277

[3] I. Noll, T. Bartel, and A. Menzel. A thermodynamically consistent phase transformation model for multiphase alloys – application to Ti6Al4V in laser powder bed fusion processes. Comput. Mech., 74:1319-1338, 2024. doi:10.1007/s00466-024-02479-z