Multi-Physics Modeling of Laser Powder Bed Fusion
– From Powder- to Part-Scale –

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ABSTRACT

Laser powder bed fusion (LPBF) of metals offers highest production flexibility, an almost unlimited freedom of design, and even the potential for local microstructure control. However, the process is governed by complex physical mechanisms on different scales, and a sub-optimal choice of parameters can lead to severe defects. To avoid such defects and fully exploit the potential of LPBF in a resource-efficient manner, more emphasis has to be put on simulation-informed workflows for process, geometry, and alloy design, requiring more elaborate, truly predictive computational modeling approaches.

Starting with an overview on our recent modeling efforts involving different physics and scales of the LPBF process such as mesoscale powder and melt pool dynamics, microstructure evolution and part-scale thermo-mechanics, the main focus of the talk will lie on part-scale approaches. In particular, scan-resolved models, i.e., physics-based models consistently resolving the laser scan path will be considered, as the specific scan pattern is known to significantly influence quantities of interest (QOI) such as temperature evolution, microstructural phase composition, and residual stresses. The fundamental computational challenge for scan-resolved part-scale simulations lies not so much in the requirements of the spatial discretization but rather in the large number of time steps necessary to resolve the laser path.

Starting from a performance-optimized thermal model [1], efficient implementations for the prediction of thermally induced microstructure compositions [2] and residual stress distributions are presented. An emphasis is placed on an implementation that best utilizes the available hardware. The implementation incorporates well-established techniques for parallel evaluation on distributed, adaptively refined meshes to balance computational work among the available CPUs. Appropriate single instruction multiple data (SIMD) techniques are utilized to speed up the evaluation times significantly. All vector accesses and updates are performed in a cache-efficient manner. Eventually, a performance analysis demonstrates the high degree of optimization of the presented approach. As an example, the proposed computational framework allows to perform thermal simulations with consistently resolved laser scan path for the complete build process of the AM Bench 2022 cantilever specimen (312 layers, 30 million spatial degrees of freedom, 50 million time steps) with times-to-solution below one day. For the same example, coupled thermo-microstructure predictions are demonstrated without significantly increasing simulation times.

REFERENCES

[1] Proell, S.D., Munch, P., Kronbichler, M., Wall, W.A., and Meier, C. A highly efficient computational approach for fast scan-resolved simulations of metal additive manufacturing processes on the scale of real parts. Additive Manufacturing. (2024) 79:103921. https://doi.org/10.1016/j.addma.2023.103921.

[2] Proell, S.D., Brotz, J., Kronbichler, M., Wall, W.A., and Meier, C. A highly efficient computational approach for fast scan-resolved microstructure predictions in metal additive manufacturing on the scale of real parts. Additive Manufacturing. (2024) 92:104380. https://doi.org/10.1016/j.addma.2024.104380.