Simulation for Additive Manufacturing
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Multiscale simulation of thermal behavior during selective laser melting of metals

Dagmar Wismeijer[1], Hanno Schouten[1], Ralph Haagsma[2], Marc de Smit[2], Jeroen Smeltink[1], René Joosten[1], Bas de Kruif[1], Robin Koldeweij[1], and Edwin van den Eijnden[1]

Equipment for Additive Manufacturing
TNO, de Rondom 1, 5612 AP Eindhoven, The Netherlands
Edwin.vandenEijnden@tno.nl, www.tno.nl

NLR-Netherlands Aerospace Centre
NLR, Voorsterweg 31, 8316 PR Marknesse, The Netherlands
www.nlr.org

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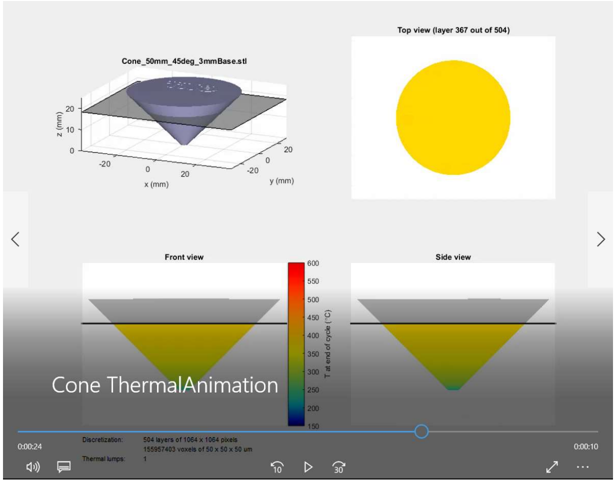
Introduction One of the key benefits of Additive Manufacturing (AM) is the possibility to produce complex integrated parts that would be difficult or impossible to produce with conventional manufacturing methods. However, without prior experience, it is hard to produce a complex part on a first time right basis. Typical issues during AM production are build failure due to internal stress in combination with a lack of supports, and geometric inaccuracies due to increased temperatures. These issues are related to the thermo-mechanical behavior of the material during the print process. Simulation of the thermo-mechanical behavior with, e.g., a Finite Element Method, gives insight in the process and allows for first time right manufacturing. As AM products are often one-of-a-kind, time effectivity of the models is of importance. Since there are magnitudes of difference in process time and length scales, the computational time can be prohibitively long. To this end, we propose a modelling method that separates two time and length scales in the thermal domain: in a coarse time and space simulation the temperature of each layer is calculated during the whole print job, and in a detailed simulation the local temperature of the melt pool is determined at the top layer. The results of both models are superposed to determine the variation in melt pool temperature during the print process. The results of the model can be used to redesign a product, change its orientation in a build job or to adapt the laser power to compensate for the changes in bulk temperature.

Model A lumped element model is proposed to predict the bulk temperature of each layer in the product during the print job. It is based on the assumption that the temperature gradient is predominantly in the build direction. Therefore, temperature gradients perpendicular to the build direction can be lumped in a single element for convex products. To further speed up the calculation process, a dynamic element size adaption scheme (based on the predicted heat transfer) is used. For powder bed fusion processes, a shell of powder around the product is represented by another lumped element per build layer. At the boundary of the powder shell and at the bottom of the product, the temperature is assumed to be constant and equal to the environment. Heat transfer can occur between neighboring layers in a single direction. The net absorbed power was determined by an experiment which also captured the loss due to radiation and convection at the top layer.

A more detailed model, based on an analytical heat transfer equation for a semi-infinite medium, is used to calculate local heat effects. This model assumes that the heat propagates through a single temperature invariant medium and was originally used to describe laser welding [1]. The model superposes the heat propagation of a propagation point source. Combined, these models capture both the short and the long distance and time effects present during selective laser melting in a powder bed.



On the left a thermal simulation of the bulk layer temperature of an inverted cone during the build job; above the printed cone.

Verification and validation

The models have been implemented as a Matlab/C/Fortran co-simulation. Verification of the coarse model with a highly detailed Finite Element method shows the validity of the lumped capacitance approach in the large time and space scale.

For validation purposes, the models were used to predict the temperature of an inverted cone and a cylinder, among others. The calculation time for a 500 layer inverted cone was 600 seconds for all the lumped layers, and 2 seconds for the melt pool temperature of the final layer. These calculations were done on a laptop with an Intel Core i7-4800MQ CPU at 2.7GHz an 16GB RAM. The lumped model predicted that products with increasing areas, such as inverted cones, will increase in bulk temperature during the build job, whereas products with constant areas, such as a cylinder, do not.

The IR emission at two wavelengths was recorded during the build of an inverted cone and a rod using a melt pool monitoring system available in the Selective Laser Melting (SLM) machine. The melt pool monitoring system was calibrated using a thermocouple in a separate experiment.

Conclusion Two models are presented that capture thermal behavior on small and large distances and time scales for laser based additive manufacturing processes. These models were validated and can be used to improve the production yield and design of products, given the current executing time of the lumped model, we envision that real-time feedforward control of the melt pool temperature is possible.

References

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