Multiphysical simulation approach for specifying material properties of additively manufactured laser heat sinks: Potentials and challenges

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Additive manufacturing of laser heat sinks enables the optimization of cooling channel geometries and the integration of various functions within a single component. Lightweight and cost-effective designs can be realized using the fused filament fabrication process. Due to this manufacturing process, only a limited selection of materials is available. An appropriate choice of filament is crucial, since the material properties have a direct influence on the resulting thermal and mechanical stress in the laser crystal. A multiphysical simulation model in combination with a parametric material model is set up to investigate the influence of the properties of the heat sink on the resulting thermal loads in the crystal.

1 Introduction

Regulating heat inside diode pumped Nd:YVO$_4$ laser crystals is still challenging in many laser applications. One approach to efficiently dissipate heat from the laser medium is to optimize cooling channels by realizing complex geometries using additive manufacturing [1, 2]. Furthermore, low cost and light weight components can be achieved by using fused filament fabrication (FFF) [3]. However, when using the FFF process, only a limited selection of filament materials is available. To avoid misalignment of the crystal, the material dependent softening temperature must not be exceeded.
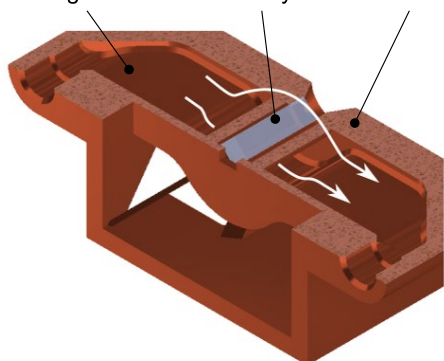

Fig 1: Additively manufactured crystal heat sink (sectional view).

This paper presents a multiphysical simulation approach to study the heat distribution inside the additively manufactured heat sink (Fig. 1) as a function of thermal material properties. This approach is used to specify minimum filament requirements.

2 Multiphysical Simulation approach

The crystal heat sink is subject to optical, thermal, fluid dynamical and mechanical effects during operation. Each domain-specific effect and their interactions influence the resulting temperature and stress distribution within the heat sink and is therefore considered in a multiphysical simulation model.

The simulation model is based on a heat source model to simulate the heat distribution in the laser crystal based on the quantum defect [4]. The optical laser diode output power of 8 W with a center wavelength of 808 nm in this example causes a temperature gradient in the crystal through the Gaussian cross section of the beam. With an additional thermal model implemented in the multiphysical simulation approach the change of the light propagation due to the thermal lensing effect of the crystal is considered. Additionally the heat propagation from the crystal through the boundary layer and the heat sink to the cooling channel is simulated. Water with a temperature of 18°C flows in the cooling channel. A CFD simulation model is used to analyze the flow characteristics and its heat convection. By iteratively changing material properties, a parametrical material model is implemented.

3 Potentials

In addition to the investigation of the material property influence on the resulting temperature, the simulation model enables the analysis of various other factors.

Critical process parameters within the laser system can be identified by parametrically changing parameters such as the optical output power of the laser diode or the inlet velocity of the cooling liquid.

By implementing different cooling channel geometries in the simulation model, the influence of design approaches on the cooling efficiency of the heat sink can be evaluated.

4 Challenges

The material properties of the heat sink depend on the printing process and its parameters, which are often not sufficiently documented by the manufacturers. In addition, the material properties are anisotropic due to the manufacturing process. This results in a deviation between the simulation model and the reality.

Furthermore, the implementation of several simulation approaches in the multiphysical model results in a time-consuming validation, since the correct representation of the domain-specific simulation models and their interactions must be verified.

5 Results

In a parameter study, the maximum temperature in the additively manufactured heat sink is calculated as a function of the thermal conductivity k of the filament and the heat transfer coefficient h between the crystal and the heat sink. An exponential decrease of the temperature with increasing heat transfer coefficient is observed (Fig. 2).
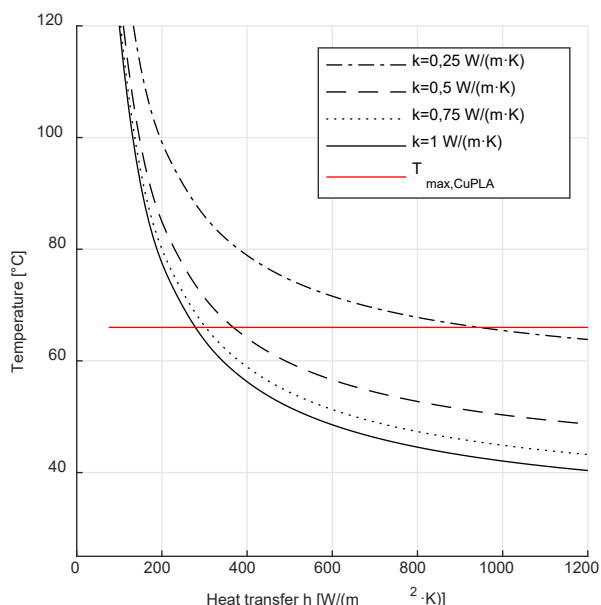

Fig 2: *Maximum temperature within an additively manufactured heat sink.*

Figure 2 also shows the softening temperature of copper-filled polylactide (CuPLA) filament which has a thermal conductivity of $k = 0.25\,\mathrm{W/(m \cdot K)}$. To avoid the softening and thus a misalignment of

the crystal, a heat transfer coefficient h of at least $1000\,\mathrm{W/(m^2 \cdot K)}$ is required.

By using filaments with higher thermal conductivity, the resulting temperature can be reduced. For example a maximum temperature of 54 °C can be achieved with a thermal conductivity of $k = 0.5\,\mathrm{W/(m \cdot K)}$ at $h = 1000\,\mathrm{W/(m \cdot K)}$.

6 Summary

With the multiphysical simulation model, the thermal loads in the crystal and in the heat sink can be analysed depending on the material properties of the filament. The fabrication of heat sinks with the FFF process is feasible if the resulting temperatures remain below the materials different softening temperature. The presented simulation environment provides a tool for validating the suitability of different filaments.

Acknowledgement

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