TOPOLOGY OPTIMIZED HEAT TRANSFER USING THE EXAMPLE OF AN ELECTRONIG HOUSING

Dennis Menge, Patrick Delfs, Marcel Töws, Hans-Joachim Schmid

Direct Manufacturing Research Center and Particle Technology Group,
Paderborn University, Germany

Contact: dennis.menge@dmrc.de

Abstract

Function integration is a key issue for an efficient and economic usage of Additive Manufacturing. An efficient heat transfer by topology optimized structures is a rarely considered approach which will be outlined with an exemplary electronic housing which has been newly designed. A commercial projector unit, whose electrical components in total produce 38 W, shall be integrated in the closed housing and passively cooled by natural convection. Topology optimized structures shall be generated in the inner part of the housing to transfer the heat homogenously from the projector components to the housing wall while simultaneously minimizing the mass. At the outside of the housing walls, lattice and rib structures are applied to increase the effective surface for heat transfer by natural convection and radiation. Furthermore, the housing geometry is optimized regarding a minimization of support structures to reduce the post-processing effort. Finally, the housing shall be built of AlSi10Mg by SLM.

Introduction

Additive manufacturing (AM) enables a high freedom in part design due to its layerwise manufacturing process. Building complex structures is possible and therefore benefits like function integration can be realized. One particular function, which can be integrated, is heat transfer. In this study a heat transfer problem for a housing of a projector unit shall be investigated. Projectors are usually cooled actively by cooling fans which certainly emit disturbing noises for the users. This study targets to develop a passively cooled housing for a projector unit and takes a rarely considered approach for heat transfer problems – topology optimization. Due to its high thermal conductivity and good processability an aluminum alloy (AlSi10Mg) will be used and processed by selective laser melting (SLM).

State of the Art

The laser melting process uses metal powder as raw material. Thin layers of powder are recoated onto the powder bed. Afterwards a laser melts the part geometry in the recoated layer. The platform lowers for one layer thickness and the production cycle starts again. Thereby, layer by layer, even very complex structures, are manufactured without additional effort. For reducing residual stress, fixing parts against warpage and supporting e.g. overhangs, support structures are needed. For this purpose the orientation of a part plays a decisive role. Support structures are totally different for different orientations of a part [1]. Inter alia therefore the SLM process underlies a variety of design rules.

Heat transfer is accomplished via two different mechanisms: heat conduction and heat radiation. Heat conduction occurs in materials with a temperature gradient. For solid and stagnant fluids heat transfer is only depending on the temperature gradient and the material properties. Heat conduction between a material and a flowing fluid is called convection. There are natural convection, where fluid motion arises from a fluid density difference resulting from a temperature difference and forced convection, where fluid motion arises from a pressure difference e.g. by a pump or fan. Heat radiation occurs without any material acting as a medium. In this case heat is transferred between two surfaces by electromagnetic radiation. Important variables to describe and calculate a heat transfer problem are the heat flow ($\dot{Q}$), the heat transfer coefficient (α), the thermal conductivity (λ) and the emissivity (ε) of a surface [2].

Topology optimization (TO) is a development tool for structure optimization which uses position and layout of structure elements. It is useful in early stages of the development process. One technology is the voxel method. The idea of the voxel method is to partition the design space in many small elements (voxel). The material behavior of each voxel is given by its density which shall be adjusted during optimization process. Voxel, which shall be deleted from the structure, will be assigned a density of 0, and voxel of desired structures will be assigned a density of 1. The TO process usually proceeds as following [3]:

1. Definition of the design space
2. Generation of an FE model
3. Definition of the design variable
4. Formulation of the optimization problem
5. Calculation
6. Interpretation
7. Realization of a part by CAD software

For TO of heat transfer problems the thermal compliance is used as optimization variable. For minimization of the thermal compliance, temperatures at knots, where heat flow is conducted into the system, are minimized for a specified heat flux. The optimized structures provide optimal thermal conductivity [4]. As an example, figure 1 shows a structure for optimal heat transfer from a given squared design space with homogeneous heat generation through the center of the top edge of a heat generating solid.

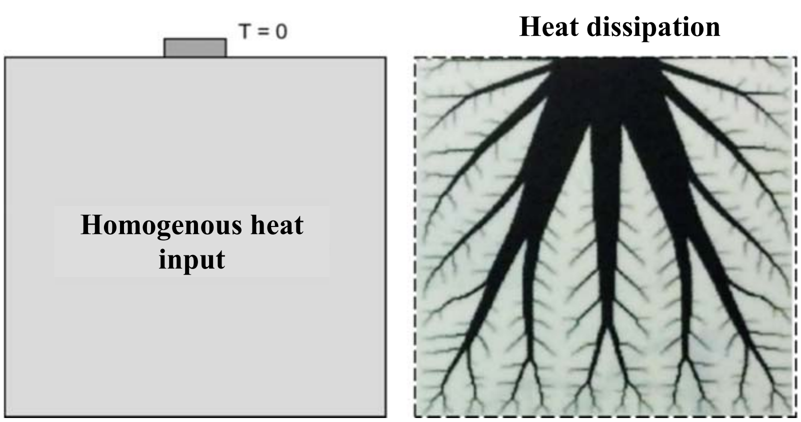

Figure 1: TO for optimal heat transfer at the center of the top edge of a heat generating solid [5]

To dissipate heat from technical components to the environment, rib structures are often used, which increase the effective exchange surface between the component and the environment. For efficiency reasons, the distance between the rib structures plays a major role. A too large distance wastes the potential to dissipate more heat flow per building volume. A too small distance can in turn cause a reduction in heat dissipation due to a disturbance of the flow situation of the cooling fluid [6]. An estimate for the selection of a suitable distance is provided by [6] using the empirical equation 1, which is valid in the case of natural convection.

Equation 1:

$$a_{Opt} = 1{,}3 * \sqrt[4]{\frac{\frac{h}{cm}}{\frac{T_W - T_{Fl}}{K}}} * cm$$

a_{Opt} : optimal rip distance for natural convection [cm]
h: rip heights [cm]
T_W: wall temperature [K]
T_{Fl}: fluid temperature [K]

Initial situation, requirements and boundary conditions

Key function of the housing should be the integration of the components and their passive cooling. Based on the specific application the critical temperatures of the various projector components (LED, Mirror-Array and Mainboard) should not be exceeded for a maximal ambient temperature of 55 °C. Further requirements are that the mountability is given, the weight of the housing should be as small as possible and the housing is tight for protecting the components against condensation and dust. Figure 2 illustrates the projector unit with fictitious limit temperatures for which the housing shall be developed.

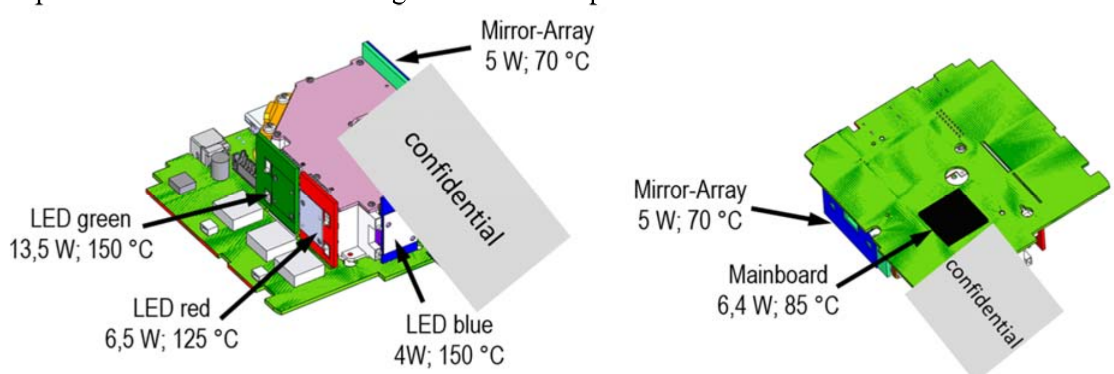

Figure 2: Projector unit

For the housing a design space (see figure 3) is given. The design space defines the outer dimensions. Furthermore, the box for power supply and the cylindrical channels for the accessibility of screw connections are non-design space.

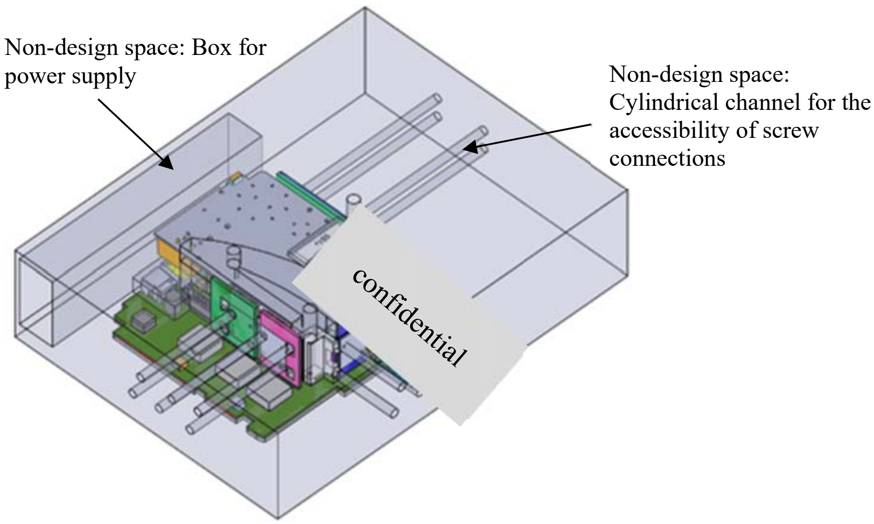

Figure 3: Design space for the projector housing

Development of the projector housing

In the concept phase, a two-part approach (top and pot system) was chosen for the housing to reduce the assembly effort and AlSi10Mg was selected as the material due to its good thermal properties (thermal conductivity of 173 W / m·K). The top of the housing is thermally isolated due to its environment in application. The pot is used for internal and external structures to cool the projector passively. The internal structures transfer the heat from the heat source of the projector to the housing walls. The external structures use the principle of surface enlargement to transfer the heat from the walls to the environment by convection and radiation. The assumption of natural convection and a steady state temperature distribution is made. The schematic sketch and operating principle of the housing is shown in figure 4.

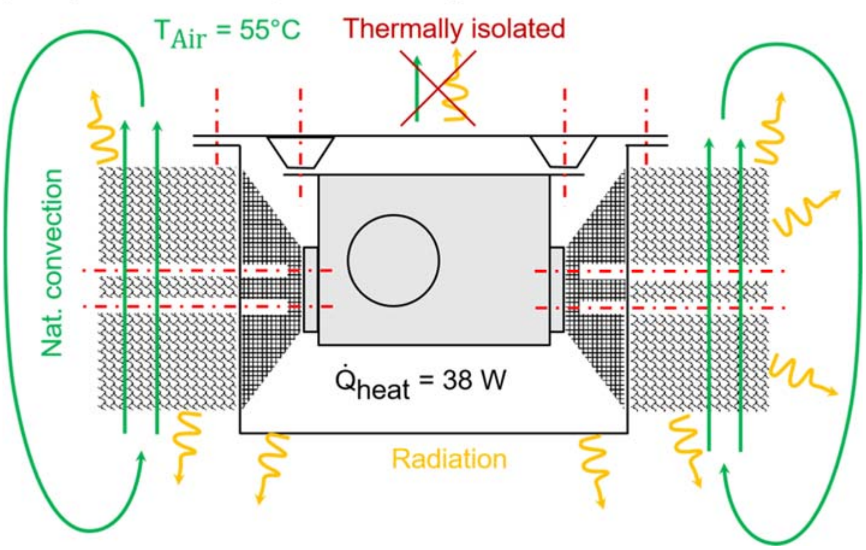

Figure 4: Schematic sketch and operating principle of the housing

For designing the housing, three steps are accomplished. First, the foundation walls of the housing are designed taking into account the design and non-design space (see figure 5). Next, the internal structures are developed by topology optimization and at last the external structures are created.

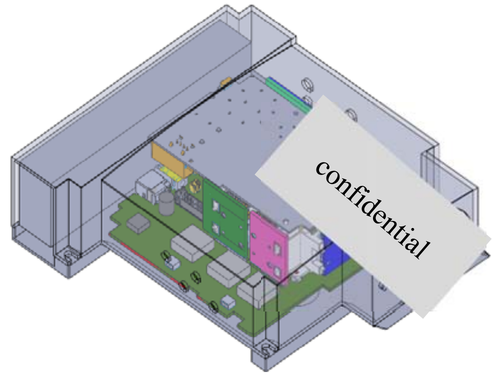

Figure 5: Basic walls of the housing

For transferring the heat from the LED´s and the mirror-array homogenously to the housing walls, structures are developed by topology optimization using the software Simlab 2017 (Altair, HyperWorks). Tetrahedral elements are used and objective is the minimization of the thermal compliance. Furthermore, the structure width is set in the range 1,5 mm to 3 mm and minimal gap size is 3 mm in order to comply with design rules for SLM by *Adam* [7]. The three design-spaces for the internal structures are shown in figure 6. The optimization is performed in two dimensions due to lower calculation effort and in order to achieve structures which can be generated easily without support structures.

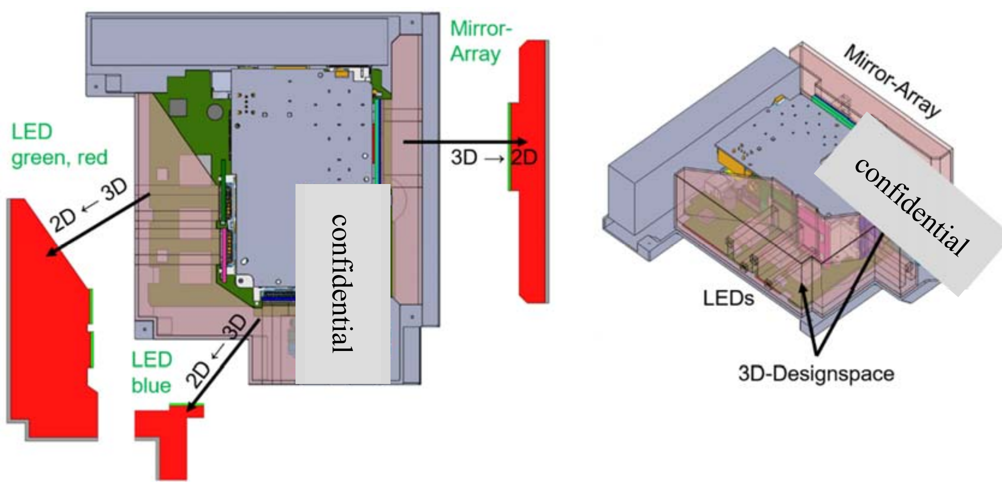

Figure 6: Design spaces for topology optimization of internal structures

Exemplarily the 2D topology optimization for the structures, which transfer the heat from the green and red LED to the housing wall, is shown in figure 7 for different mass fractions as pre-specified condition (20 %, 30 %, 35 % and 40 %).

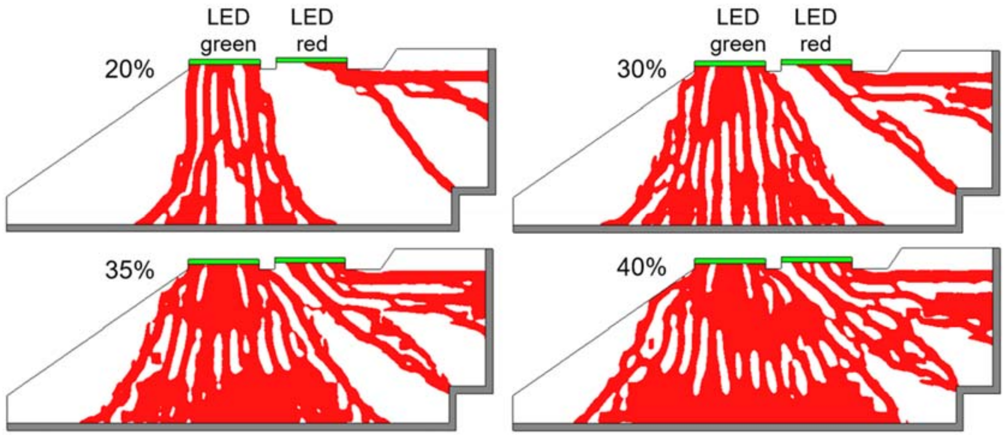

Figure 7: 2D topology optimization for the green and red LED with different mass fractions

To decide which mass fraction should be used for the internal structures, the heat transfer of these structures (extruded in 3D) are examined numerically with Abaqus. Target of the examination is the determination of the temperature difference between electronic components and housing wall in correlation to the mass fraction. The results of the calculation are shown in figure 8.

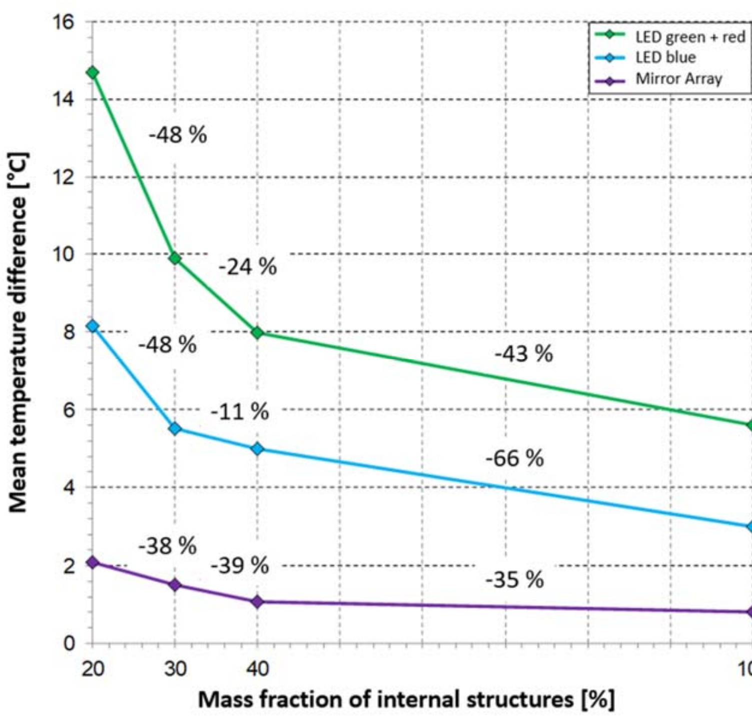

Figure 8: Mean temperature difference in correlation to mass fraction of internal structures

The decrease of the temperature difference between the mass fractions of 20 % to 30 % is relatively high for all three internal structures (38 % and 48 %). Between a mass fraction of 30 % and 40 % the temperature of the LEDs drops by a smaller fraction of 11 % and 24 %. The decrease in the mirror array is still high (39 %). The reference models (mass fraction of 100 %) show that the temperature differences could still be reduced by a further 35 % to 66 %, whereby the increase in weight of the internal structures would also more than double. For this reason, the structural curves resulting for a mass fraction of 30 % are selected for the internal structures and implemented in the housing (see Figure 9).

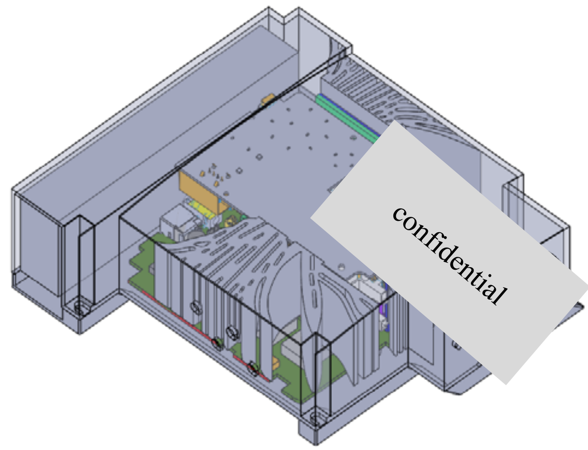

Figure 9: Housing with integrated topology optimized internal structures

For the external structures, the approach was chosen to use structures that have a high efficiency, a large ratio of surface to volume and which can be produced without support structures. The basic idea for the design is the creation of rod structures which form vertical air flow channels and do not hinder the resulting flow of natural convection. The focus here is on improving heat transfer by convection, i.e. increasing the surface. Radiation plays only a minor role and it can be shown retrospectively, that the ratio of radiative heat transfer to heat transfer by natural convection does not exceed approx. 10 % for the given boundary conditions. Three unit cells have been designed for the differently located outside areas of the housing (see figure 10) by using the formula for optimal rip distance with natural convection (equation 1). The air temperature was assumed to be 55 °C. For the wall temperature a temperature of 68°C, which is below the maximum operating temperature of the critical projector component, is selected. To obtain an even basic shape of the vertical flow channels, a square pattern is chosen. The optimum distance corresponds to the height of the structure. Using an iterative procedure, a distance of 6 mm is determined from equation 1. The rods of the unit cells have a circular cross section. The main rod of unit cell 1 runs at an angle of 45 ° to the xy plane to avoid support structures. Unit cell 2 has three central rods in the y-direction which start on the housing wall. This is due to the 45° (to xy plane) angled rods in x-direction, as they only cut every second central rod. Since the elementary cell 1 does not conduct the heat in the x-direction on the shortest way (which would be at 0° orientation) to the outside, the efficiency decreases relatively strongly with increasing distance in x direction. For this reason, a third elementary cell is designed, which transfers the heat more appropriately over a greater length in x direction on the side of the mirror array. Elementary cell 3 consists of a rib with additional cross rods in the y-direction. After a certain distance, the lighter elementary cell 1 should again be used for the remaining section in x direction.

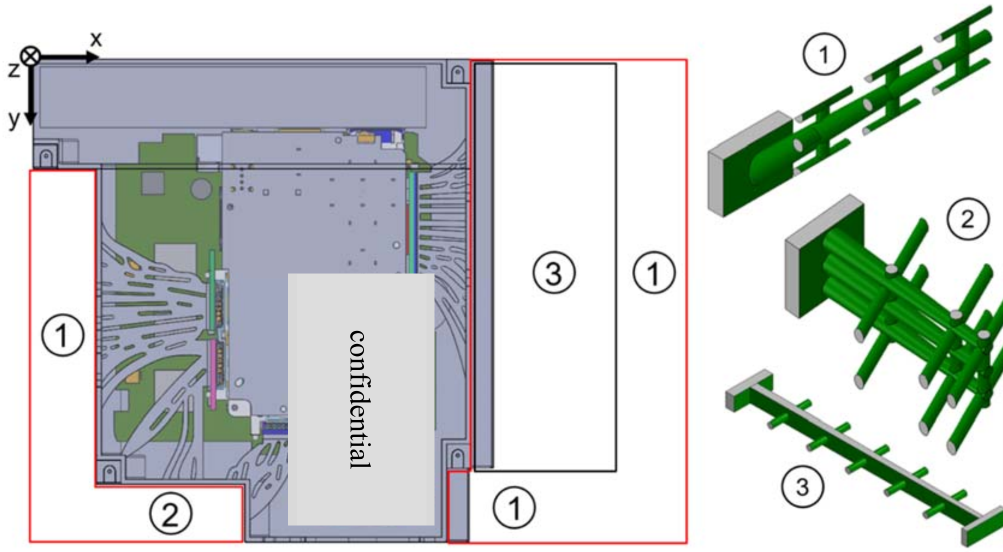

Figure 10: Unit cells of external structures in different areas

The model of the final housing is shown in figure 11. Figure 12 displays the housing made of AlSi10Mg with SLM. On the left hand side, the housing is still on the building platform to show the building orientation and the little amount of support needed.

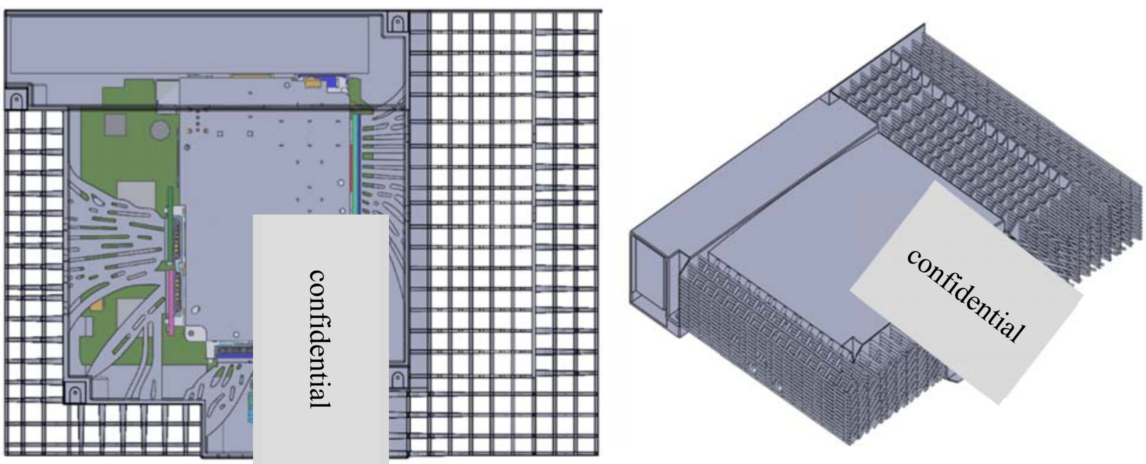

Figure 11: Projector housing with internal and external structures for passive cooling

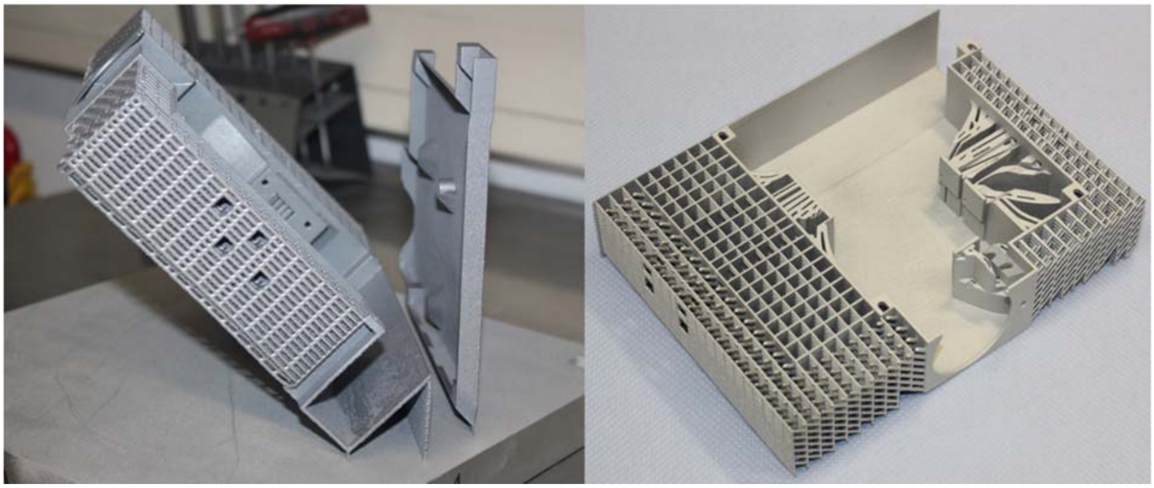

Figure 12: Projector housing manufactured by laser melting.

Reanalysis

Further, a reanalysis of the developed housing is performed. Figure 13 shows a simulation of the temperature distribution for an external heat transfer coefficient by natural convection of 10 W/m^2·K, an emissivity of 15 % and temperatures (air and environment) of 55 °C exemplarily. The transfer coefficient and the emissivity are assumed values since they are unknown. According to literature [8], the heat transfer coefficient by natural convection is expected to be between 2 and 20 W/m^2·K.

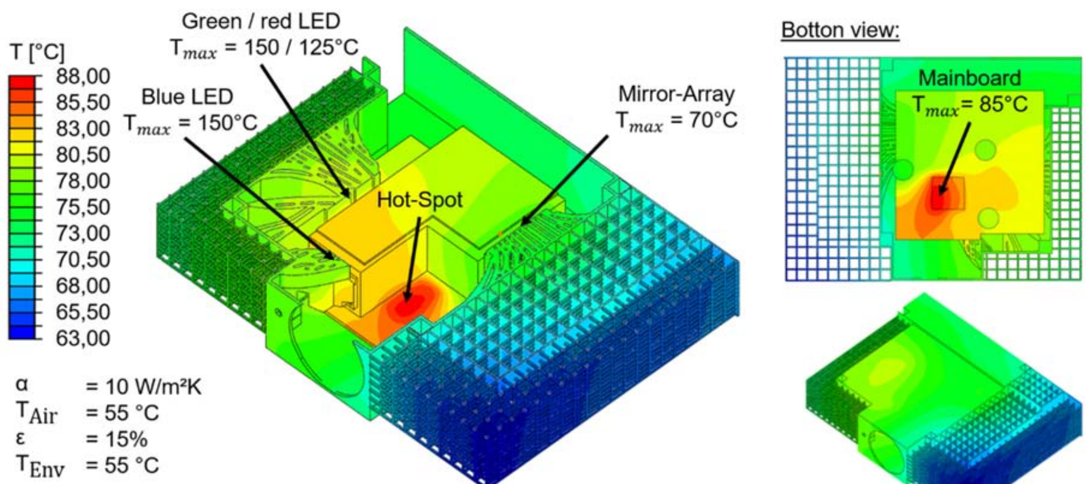

Figure 13: Temperature distribution

The resulting temperature field is between 63 °C and 88 °C. The maximum temperature of 86 °C occurs on the mainboard and is close to the specified maximal operating temperature of 85 °C. The LEDs all have approximately the same temperature of 78 °C and the maximal operating temperature is well observed (125 / 150 °C). At the surface of the mirror array a temperature of 77 °C is predicted which is close to the maximally allowed operating temperature of 70 °C as well.

For the above mentioned assumed values, the maximal operating temperatures cannot be fully observed for all components. However, if the transfer coefficient by natural convection is varied within reasonable boundaries, figure 14 shows the resulting surface temperatures of the mirror array and the mainboard since they have been identified to be critical from the previously shown simulation. For an increasing transfer coefficient, the temperatures decrease as expected. The maximal operating temperatures of all components can be deserved if the value of the heat transfer coefficient is 20 $W/m^2 \cdot K$.

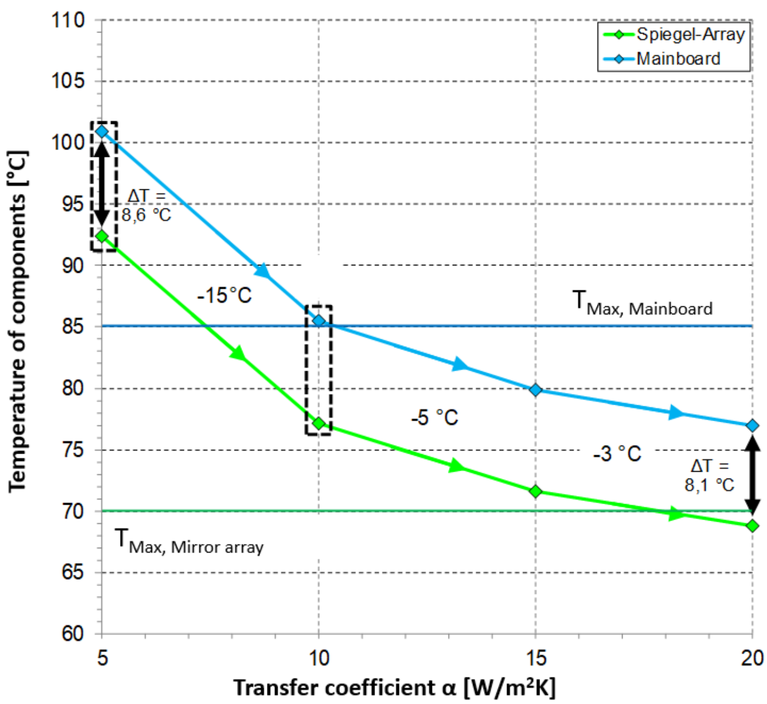

Figure 14: Influence of the heat transfer coefficient α on the component temperatures

Conclusion and outlook

Topology optimization is a feasible method to generate structures for increased heat transfer. In the present work a projector housing, which can be manufactured by SLM, has been developed. The housing dissipates heat from the electronic components. With the help of a topology optimization, low weight structures could be found, which distribute the heat suitably and homogenously from the projector components to the housing walls. Through the application of surface-enhancing external structures, the effective surface for heat transfer by convection and radiation could be increased. Also a numerical model of the complete mounted housing including the projector unit was implemented. The simulation results showed that the designed housing can dissipate the heat generated during operation. However, the use of the projector for an ambient temperature of 55 °C is only recommended to a limited extent due to the unknown heat transfer coefficient.

For further research, the conclusions drawn from the numerical calculations will be verified experimentally. The housing will be post-processed and the projector will be implemented. Therefore, contact areas should be milled and heat conducting paste should be applied. The projector will be started up and the resulting temperature distribution will be recorded using a thermal imaging camera. Furthermore, the housing could be heat treated for better thermal conductivity or anodized for higher emissivity.

Acknowledgement

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