Design and manufacturing of a cylinder head by laser powder bed fusion

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Abstract. Nowadays the reduction of fuel consumption is the most important challenge for engine development. Laser Powder Bed Fusion (LPBF) as an additive manufacturing process with its implied design freedom makes it possible to reduce combustion emissions, increase engine efficiency and respond specifically to customer requirements. In this work, the outstanding degree of freedom of LPBF is exploited for a new design concept for a cylinder head of an engine in automotive industry in order to address further reduction of fuel consumption through improved cooling performance. Within the given installation space and under consideration of the existing mounting and connection positions, the design concept was developed, subsequently manufactured and reworked. In order to develop a design that meets the LPBF requirements, both the potential of the LPBF using the geometric degrees of freedom as effectively as possible and the limitations are considered. The opposing design drivers between exploitation of potentials and limitations in LPBF are achieved by an iterative design process supported by an own developed design tool. With the new design concept, a reduction of the metal temperature in the cylinder head of approx. 25 K is achieved, verified by simulation.

1. Introduction

Nowadays, the reduction of fuel consumption is the most important challenge of the engine development, and this determines most design decisions [1]. Additive manufacturing (AM) with its implied design freedom makes it possible to reduce combustion emissions, increase engine efficiency and respond specifically to customer requirements. Moreover, this technology has a high potential for future manufacturing, but the application is not yet standard in automotive engine components: Metal AM opens new development opportunities for powertrain components. The most widely used AM technology for metals is Laser Powder Bed Fusion (LPBF) [2]. For the LPBF process, CAD-information and a high-power laser beam are used to create three-dimensional metal parts by fusing fine metal powders. LPBF offers a great potential to add further functionality to the parts and to increase performance. As it can easily generate integrated hollow or lattice structures for the LPBF-fabricated parts, the volume and weight of the component can be reduced and/or simultaneously the surface can be increased (e.g. for highly-improved heat transfer). This technology opens the horizon to entirely new design approaches to reduce current production and lead times and to bring down production costs in the future. Using the new approaches, completely novel and multifunctional parts can be designed.

In this work, the outstanding degree of freedom of LPBF is exploited for a new design concept for a cylinder head of an engine in automotive industry to address further reduction of fuel consumption through various measures. Therefore, cooling performance (combustion knock avoidance) and
manufacturing quality in parallel are addressed. Within the given installation space and under consideration of the existing mounting and connection constraints, the design concept was developed, subsequently manufactured and post-processed to be evaluated on a test bench simulating real operating conditions in the future.

2. Laser Powder Bed Fusion

The process steps of LPBF are shown in figure 1. The material as powder particles is processed and completely melted locally and selectively by a laser beam according to a digital slice model of the part. The layer forms a dense material after solidification. A relative density of over 99.5% is achieved if the correct process parameters are chosen, and the layer thickness is usually approx. between 30 and 60 µm. For a detailed description of the process see [3].

Due to ongoing research, the number of processable materials increases. Nowadays, there exists a wide range of different commercially available materials, such as aluminium alloys (e.g., AlSi10Mg, AlSi12), stainless and tool steels (e.g., 1.4404, 1.4542, 1.2709), Nickel-based alloys (e.g., Inconel 718 and 625) as well as Titanium (e.g., Titanium Grade 2, Ti6AlV4) [4, 5].

2.1. The LPBF design restrictions

LPBF as an AM process offers a high degree of design freedom compared to conventional manufacturing processes such as milling or casting. However, there are also design restrictions for the parts produced by LPBF. The rapid heat input and cooling cause the shrinkage of the bonded consecutive layers leading to residual stresses in the part. For overhang features, these residual stresses result in deformation. When the overhang angle is below a critical angle \( \alpha_{\text{crit}} \) this deformation can lead to failed built parts caused by high deformation and crash between recoater and part. To avoid it, support structures are used to counteract the stresses and to dissipate heat (figure 2) [6]. To prevent deformation
of the parts after the removal of the support structures, the components might be heat treated after the process, depending on the material.

![Figure 2. Support structures and critical overhang angle](image)

After the LPBF process, the post-processing of the parts on the substrate plate is required. On the one hand, the support structures must be removed mechanically, on the other hand functional surfaces with high surface requirements have to be post-processed by milling or drilling. In general, the LPBF components have a low surface quality ($Ra = 10 - 20 \, \mu m$) due to sintered powder particles and/or the stair stepping effect which results from the layerwise nature of the manufacturing [6].

For applications where a cooling fluid is used, such as cylinder heads, it is important that no powder particles or support structure residues are left in the part, as these could damage the components in the cooling system. Therefore, cooling systems should be designed such that either no support structures are required or that the support structures can be removed after the process [7]. The concept in this work is to utilize the properties of the support structures and to employ them to improve the cooling properties of the cylinder head. For this purpose, internal cooling structures are designed, which on the one hand guarantee the processability of overhanging structures by LPBF and on the other hand, improve the cooling characteristics of the cylinder head.

The LPBF process has design restrictions, for example, the wall thickness and gaps are limited to a minimum (approx. 0.3 mm in the build direction). Bore diameters 90° to the build direction can be produced without support structures at a minimum of no less than approx. 1 mm and at a maximum of no more than 10 mm. However, these restrictions depend on the build direction, the processed material and the characteristics of the machine. A summary of the design restrictions for the LPBF process of different materials can be found in [7, 8, 9, 10, 11].

2.2. **Visual programming to exploit LPBF design potential**

Computer Aided Design (CAD) plays an integral role amongst various industries and most notably in mechanical engineering. Common CAD software products for mechanical engineering are built around the idea of a hierarchical design tree that allows the user to chronologically track modifications made to the model [12]. Although that structure is desired and well suitable for geometrically static parts within serial production, it does not provide the ability to exploit the design possibilities of AM. The geometric degree of freedom and the toolless production has led to unknown potentials in mass customization and creation of complex structures. Mass customized parts often consist of a main body design while additional features are customized and individually designed. With an increasing demand of mass customized parts, the manual workload to individualize the parts while preventing duplicates by exploiting the patterns exceeds the natural capabilities of creativity as well as boundaries of cost efficiency. The same problems apply for complex geometries. As an example, lattice structures consist of multiple struts that compose a unit cell which are, in the simplest case, repeated to fill a certain
The explicit construction of every lattice strut would lead to an enormous workload and computational effort. Visual programming environments such as Grasshopper 3D, which are originally designed for architecture, provide the user with the ability of designing 3D geometry using algorithms. These algorithmic modelling is not only well suited to automatize the aforementioned tasks, but further allows for efficient iterative design approaches that are often encountered in AM. One or multiple inputs in the form of geometries, parameter controls and others relate to a generative algorithmic model that produces outputs based on the connected functions within the algorithmic model. An integration of random number generators into the algorithmic model allow for the generation of a given quantity of geometries, that are individual and distinguishable concerning certain design aspects, while still sharing the general shape and connection points, which allows for an efficient customization [14]. As an input and output-based modelling approach, the algorithmic unit can be built in a manner, that the implemented modifications apply to inputs of different shapes which enables iterative modelling approaches. If implemented correctly, later changes in the base model are easy to handle due to the flexible input and require little to no adjustments to get the desired output model. For repetitive tasks on varying geometries, such as the generation of lattice structures inside of several different parts, the necessity of only a single algorithmic model greatly reduces the workload. This advantage also applies for other design adjustments such as offsets and fillets where the same design adjustment is going to be applied to several different base geometries.

3. Approach
To achieve the goal to design and manufacture the cylinder head, the three-step process shown in figure 3 is applied. In the first step, a material suitable for the specific application is selected and the process parameters as well as static and dynamic mechanical properties are developed for the selected material processed by LPBF. Once the material is selected and the mechanical properties are determined, the cylinder head is designed. To develop a design that meets the LPBF requirements, both the potential of the LPBF using the geometric degrees of freedom as effectively as possible and the design constraints are considered. The opposing design drivers between exploitation of potentials and constraints in LPBF are achieved by an iterative design process. The use of Grasshopper 3D allows for an efficient iterative design process in mainly two aspects. While the cylinder head base model was still undergoing geometric changes within the design space, the model was developed with an earlier version of the cylinder head while still being fully compatible with the final geometry.

| Material | Design | Manufacturing |
|----------|--------|---------------|
| Mechanical properties | LPBF design potentials | LPBF process |
| Process parameters | satisfy | Post processing |
| | exploit | |

**Figure 3.** Schematic illustration for the design and manufacturing of an LPBF-suitable cylinder head design
After completion of the cylinder head design by the project partner the final model was used as the input to the Grasshopper 3D model and the rib structures were modelled according to the new geometry without further adjustments. Secondly, the use of slide controls for the ribs parameters enable intuitive and fast rib adjustments according to the simulation results of every iteration step. Finally, the component is manufactured by LPBF on a commercially available LPBF system, X-Line 2000, and post-processed by milling.

4. Material
In the first step, the potential alloys for the cylinder head are identified. For this purpose, aluminium alloys that can be processed with LPBF are investigated by a literature review. The following alloys are investigated: AlSi12, AlSi7Mg, AlSi10Mg, AlSi9Cu3, AlSi9Cu3, AlMgScZr, AlMg4,5Mn0,4, Al-12Si, and AlMg1SiCu. Based on the four selection criteria mechanical properties, processability, cost, and availability one alloy is selected. For mechanical properties Young’s modulus, tensile strength and ultimate elongation is considered. The objective is that the mechanical properties meet or exceed the target properties given for the casting alloy. From the alloys that achieve these target properties, AlSi10Mg is selected for the cylinder head because of its good processability, availability and thus low costs. For the selected material, process parameters for laser power up to 1kW are developed to fabricate specimen with a density greater than 99,5%. To achieve suitable material properties for the given use case and to reduce thermal stresses leading to the deformation of the part, a heat treatment process is investigated. Therefore, two different heat treatments are applied on the test specimens and mechanical properties are evaluated. Between the investigated heat treatments, stress relief annealing was identified as the most suitable one, as it showed the best balance between mechanical properties and low deviation over the specimen at different temperatures. The stress annealing consists of a heat-up, hold and cool-down phase. First, the part is heated up to 240° C in 1 hour. After a hold time of 6 hours, the component is cooled down to 100° C in the oven and then completely cooled in ambient air to room temperature. For the selected material under the selected heat treatment, the mechanical properties are determined. For the characterization of the material properties, the density, hardness, static mechanical properties (tensile strength, brake elongation, yield strength), thermal properties (thermal conductivity, specific thermal capacity) and dynamic mechanical properties (HCF) are investigated and simulated. Measured material properties from the tensile test are given in table 1. The measured thermal properties are given in table 2. All other properties for the simulation are taken from literature.

| Material property | RT | 150°C | 200°C | 250°C |
|-------------------|----|-------|-------|-------|
| Tensile strength  | Ø  | 311.00| 247.75| 210.75| 171.13|
| [N/mm²]           | s  | 27.22 | 13.89 | 27.12 | 7.90  |
| Yield strength    | Ø  | 163.00| 152.00| 138.75| 127.63|
| [N/mm²]           | s  | 7.55  | 6.48  | 7.89  | 4.10  |
| Elongation        | Ø  | 5.67  | 13.45 | 18.20 | 23.03 |
| [%]               | s  | 2.15  | 3.85  | 6.52  | 5.05  |
Table 2. Results from laser flash method measurement of stress relief annealed test specimens of AlSi10Mg

| Temperature [°C] | Thermal conductivity Z-direction [W/(m K)] | Std. deviation [W/(m K)] | Thermal conductivity XY-direction [W/(m K)] | Std. deviation [W/(m K)] | Specific thermal capacity [J/(g K)] | Std. deviation [J/(g K)] |
|------------------|-------------------------------------------|--------------------------|-------------------------------------------|--------------------------|-----------------------------------|--------------------------|
| 23               | 162.9                                      | 7.2                      | 154.6                                     | 7.7                      | 0.885                             | 0.033                    |
| 150              | 163.6                                      | 6.3                      | 154.4                                     | 2.1                      | 0.940                             | 0.024                    |
| 200              | 165.4                                      | 6.1                      | 154.9                                     | 2.9                      | 0.967                             | 0.025                    |
| 250              | 160.5                                      | 3.5                      | 152.2                                     | 1.2                      | 0.965                             | 0.018                    |

5. Design Process
The most promising approach to fully exploit the technological and economical potential of LPBF is to apply different design strategies like lightweight design, functional integration or improvement, monolithic design, or customized mechanical properties, which are feasible due to the great design freedom. While exploiting the advantages of the technology, the design restrictions that apply to LPBF parts must also be considered. As shown in figure 2, a main consideration when targeting complex parts as a cylinder head are cavities that can be found all over the part. In the first step, the main orientation of the cylinder head towards the build plate is determined, to find an optimal orientation where the number of critical surfaces in terms of LPBF is reduced. The remaining critically surfaces with an overhang angle below the critical angle, need to be addressed. Due to the complexity of the part, many of these overhang-violating surfaces can be found inside the water jackets of the cylinder head as well as in the combustion in-take and out-take. With high proximity to the combustion cavities, the highest potential for improved cooling performance lies in the lower water jacket. Therefore, the following work shows the design process for the cylinder head.

Figure 4. Schematic illustration of the parametric design model

While the design of the main body of the cylinder head is generated with conventional CAD software products, the design approach for the structures must meet the requirements of an iterative and LPBF-
suitable approach. The used approach must provide the ability to easily adapt to changes that are made to the main body of the cylinder head during the development of the structures. In addition, the design approach must allow for a fast generation of differently parametrized structures and the ability to quickly adjust the structures according to the simulative validation results. The use of generative algorithms within the parametric visual programming environment of Grasshopper 3D was identified as suitable and likewise necessary to achieve the desired flexibility.

The CAD-file of the cylinder head serves as the input for the generative model. Before implementing the model, the main adjustable parameters need to be identified. To allow the water inside the jacket to flow without problematic dead ends or strong narrowing areas, the offset of possible rib structures from the contour of the cooling jackets is a necessary parameter. The water flow is furthermore significantly affected by the cross section of free water flow, and thereby directly by thickness and spacing of possible rib structures. The named inputs are designed as slide controls within the Grasshopper 3D environment.

With the use of a non-planar intersection plane, the contour of the cooling jacket is derived from the CAD model of the cylinder head. The inner offset of the cooling jacket contour is now computed with the offset parameter, allowing easy modification later. The parameters of rib thickness and spacing are then used to generate an array inside the contour offset which represent the center line of individual ribs. With the use of the parameters of thickness and spacing, the cross section of each rib is defined. Starting with a rectangular cross section which would lead to high flow resistance, the generative model allows for a chained group of modifications such as fillets. The ribs fillet radius can also be modelled as a variable input for later modification. With the cross sections defined, the ribs can be extruded to exceed the length of the cooling jacket. The 3-dimensional cooling jacket is then used for a Boolean split operation, to cut the ribs to exact length. An example rib model is shown in figure 5.

![Figure 5. Cooling Struts inside the water jacket](image)

With the described model, a variety of combinations in terms of rib thickness and spacing were derived just by adjusting the slide controls to the desired values. Moreover, the input-output nature of the parametric algorithm allowed the continuous development of the cylinder head without causing incompatibility. To meet the requirements concerning the LPBF process in terms of support structures, the rib parameters were chosen from a parameter grid that ensured that the remaining critical faces are sufficiently supported and producible with LPBF. With an initial set of rib variations, CFD simulations were performed to quantify the cooling performance and showed significant improvements in the temperature filed of the cylinder head. Furthermore, the FEM simulations were utilized to ensure
sufficient stiffness to sustain the mechanical stresses caused by combustion. With multiple iterations of simulation and model adaptation, an ideal set of model parameters were determined, and the rib model was finalized.

6. Production and post-processing
In the final step, the cylinder head is manufactured by LPBF. Part of this manufacturing process is also the pre-processing, which means slicing and data preparation, and post processing. The post-processing includes heat treatment, removal of support structures and powder, and milling of functional surfaces and interfaces. Since the cylinder head is to run under real conditions, the same mechanical post-processing is applied as for conventional produced (casting) cylinder head, since the interfaces to the surrounding parts and functional surfaces are not adapted. The cylinder head is manufactured on a X-Line 2000 R system. The LPBF process time was around 12 days. To achieve the required geometric accuracies for the post-processing, the data, which is transferred to the LPBF system for the production, is scaled to compensate for expansion under the preheating temperature (200°C preheating). In addition, functional surfaces are provided with a post-processing offset. The cylinder head built in this project meets all the criteria for being installed on a real engine and used under real conditions. With the new design concept, a reduction of the maximum temperature in the critical areas of the cylinder head by approx. 25 K are achieved, verified by simulation of the coolant side metal temperature. In figure 6, the post-processed cylinder head is shown.

7. Summary
LPBF is an AM technology that offers new design freedom for metal parts to increase the performance of these parts. To exploit this potential, the design constraints of LPBF and the use of suitable design tools and methods are considered. These challenges and possible solutions are shown within this work by the example of a cylinder head. The visual programming language Grasshopper 3D was used to develop a generative and parametric in-house design tool for cooling structures of a cylinder head. Considering the material properties and production-oriented design, a cylinder head was produced that fulfills all functions required for the use under real conditions.

In the first step, only a specific feature, the water jacket, is considered and optimized to improve the function of the cylinder head. In order to exploit the full potential of the LPBF for this component, a complete redesign is necessary. This not only improves the manufacturability of the cylinder head, e.g. by reducing the number of support structures and thus reducing the process time, but also provides
Further functional improvements can be found, for example, in the lightweight construction by reducing the wall thickness compared to conventionally cast cylinder heads.

The process time for the LPBF cylinder head is 12 days. This significantly exceeds conventional production (casting). Even with current improvements in productivity (e.g. multi laser systems, shorter coating times), the production time cannot be reduced to a competitive level. One approach to reduce process time and costs is the use of hybrid manufacturing. The cooling struts are only needed near the combustion chamber, where the increased cooling performance is required. In hybrid production, a base body part is casted. The geometrically complex area is produced by direct buildup on this base body part using LPBF. This achieves a significant reduction in process time.

Acknowledgments
The studies for this work are carried out in cooperation with the Ford-Werke GmbH in Cologne, Germany. Thank you for your support and willingness to explore new paths for established technologies.

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