Design optimisation of a cylinder head with additive manufacturing

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Abstract

For many thermally and mechanically high-loaded components, such as the cylinder head, cooling and thermal management are key factors for function and durability. Ideal cooling systems have complex internal structures that cannot be produced economically using conventional manufacturing methods. Higher design freedom within additive manufacturing offers high potential to create cooling structures that are close to the optimum. This study investigates how additive manufactured cooling structures can improve the function and durability of thermally and mechanically high-loaded components and how they can be methodically integrated into the design using the example of a 1.5 L I3 gasoline turbo engine cylinder head.

Exploiting the design possibilities of additive manufacturing to optimize thermally high–loaded parts

The efficiency, function and durability of thermo-mechanically high-loaded parts can often be increased by improving thermal management, e.g. through enhanced cooling. Cylinder heads, for example, can be improved not only in terms of combustion efficiency and thus fuel consumption, but also in terms of durability by increasing the number of possible temperature and combustion cycles. (Kohler 2006) Cylinder heads are typically made of aluminum alloys. Since the cylinder head is mounted directly onto the pistons, there is a thermal load from combustion and a mechanical load from the piston pressure. Cooling is achieved by longitudinal or transverse flow of cooling water through water jackets (van Basshuysen 2010). The greatest challenge in cooling is to achieve the most efficient and homogeneous cooling of the combustion chamber face.

One possible method for improving cooling performance is near-net shape cooling with simultaneous reduction of the combustion chamber deck temperature, as well as increasing the dissipation of process heat into the coolant. The object is to optimize the design by integrating ribs inside the water jacket. Integration of these ribs significantly increases the design complexity and thus the manufacturing complexity using casting. Applying Additive Manufacturing (AM), filigree and complex internal structures can be manufactured economically. The most common AM process for metals is Laser Powder Bed Fusion (LPBF). (Wohlers und Campbell 2017) In addition to the increased degrees of freedom, LPBF still has design constraints, which have already been outlined in various publications and standards (VDI 3405 Blatt 3:). By exploiting the LPBF design potentials, a cylinder head with the best possible cooling properties using optimized ribs in the water jacket is to be designed, manufactured, and tested. The tests are performed with a 1.5l I3 GTDI bottom engine under real load conditions. Two approaches are presented for the integration of those ribs.

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Approaches and Methods to design optimized cooling ribs

The integration of internal ribs to improve cooling performance is demonstrated with the design of a cylinder head of a downsized 1.5 L I3 gasoline turbo engine with direct injection. Based on a literature research AlSi10Mg is selected to manufacture the cylinder head based on the criteria

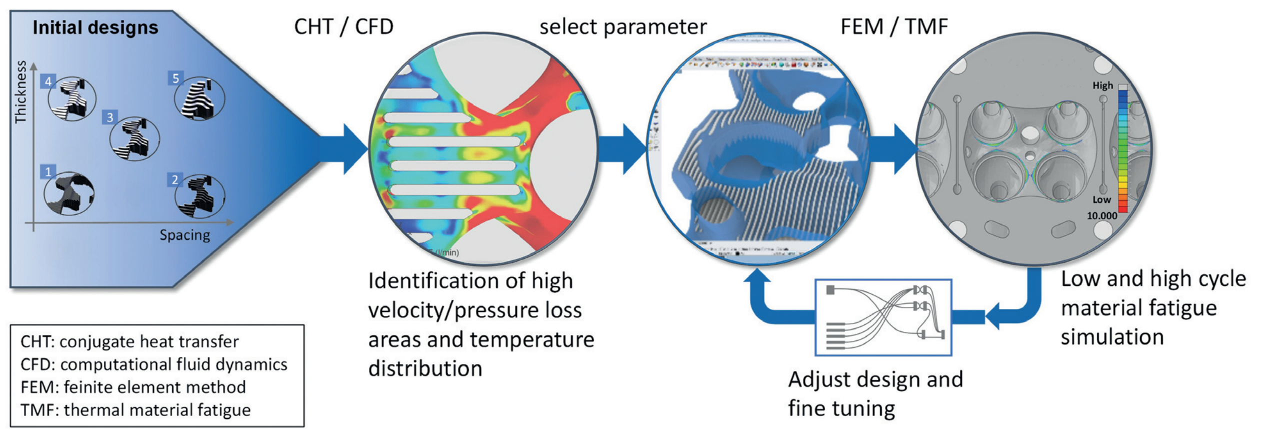

Fig 1. Schematic representation of the first approach: parameter variation based on simulation

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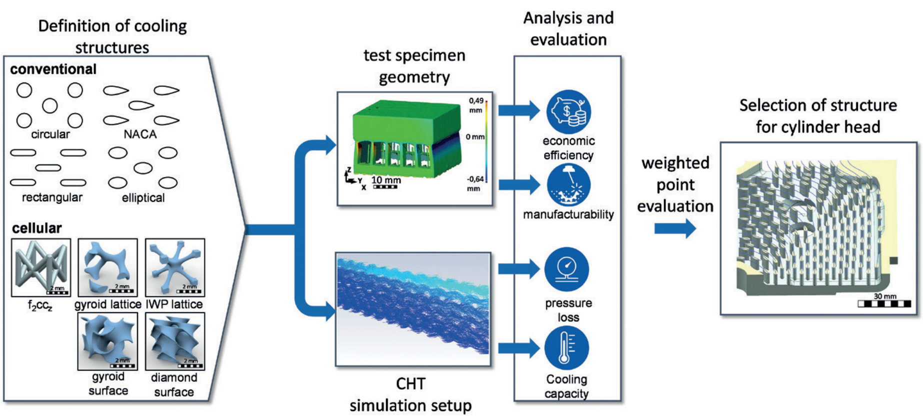

Fig 2. Schematic representation of the second approach: general study of cooling rib structures

mechanical properties, processability, cost and availability. To design the cylinder head, the mechanical and thermal properties of the LPBF-produced material were first characterized. The results are published in Design and manufacturing of a cylinder head by laser powder bed fusion (Willkomm et al. 2021).

For the integration of the ribs into the water jacket, two different approaches - 1. parameter variation based on simulations, 2. general study of cooling rip structures - were carried out, which are described in more detail below.

Parameter variation based on simulation

For the first approach, an initial design of the cooling ribs is defined. Elongated cooling ribs are defined to increase the cooling surfaces and to ensure the flow of the cooling fluid. The rib thickness and the spacing between the ribs are defined as adjustable parameters. Several designs with different thickness and spacing are created. For each of these designs conjugate heat transfer (CHT) and computational fluid dynamic (CFD) simulations are performed to investigate and compare the pressure loss and temperature distribution. The rib structure with acceptable pressure loss and simultaneous improvement of the cooling performance is selected and integrated into the cylinder head model. A final iterative adaptation, e.g. adaptation to the design space and addition channels to avoid stagnant flow conditions, of the rib structure is carried out. Material fatigue is investigated using finite element method (FEM) and thermal material fatigue (TMF). By integrating the rip structures using a design scripting model, the required adaptations can be carried out efficiently. A detailed description of this model is published in (Willkomm et al. 2021). A schematic representation of the procedure is shown in **Fig 1**.

General study of cooling rib structures

The second procedure describes a general study of rib structures (s. **Fig 2**). Based on this study, the appropriate rib structures for the application can be selected. First, the requirements for the rib structures are defined and possible rib structures are selected from the literature. The investigated structures include rib structures with constant circular, elliptical, rectangular and NACA-profile (cross section see Figure 2) cross-section over height as well as the cellular structures f2ccz lattice structure, and the triple periodic minimal surface (TPMS) structures diamond surface, gyroid surface and lattice and IWP lattice structure.

All structures are analyzed and compared to each other in terms of manufacturability using LPBF, economic efficiency in design and manufacturing, cooling capacity and pressure loss. The test geometry in the center of **fig 2** is used to investigate the manufacturability and economic efficiency. For economic efficiency, the file size and build-up times for each structure are compared to each other. For the evaluation of the manufacturability, the deviation of the LPBF manufactured specimens from the CAD files is evaluated. The picture in **fig 2** (center) shows the result of the comparison of CAD files and 3D scan for the rib structure with rectangular cross section. The cooling performance and pressure drop are investigated and compared to a simulation model using CHT simulations. By means of weighted point evaluation, a suitable structure can be selected for the respective application, e.g. in the water jacket of the cylinder head. In this way, different rib structures can be selected for different areas, e.g. near and far from the combustion chamber.

For comparability, the same relative density was used for all structures (10%, 15%, 20%). Due to the lattice architecture, the cellular structures have lateral struts in comparison to the ribs with a constant cross-section. In **Fig. 2** (left), the cross sections of conventional structures are shown. The rib structures are created by extrusion in the z direction. This results in a higher stiffness and thus a better manufacturability. The increased complexity of these structures results in a larger file size for representation and a longer exposure time for manufacturing so to higher costs. Cooling performance is higher for the cellular structures due to the larger cross-sectional area. The pressure drop is lowest for the rectangular and NACA cross-section ribs because of the low structure density and low flow resistance.

Conclusion

The two procedures described above are used to generate rib structures at different positions in the water jacket of the cylinder head. It is shown that the procedure with simulation-based parameter variation results in a significant improvement in thermal management within the combustion chamber. A LPBF manufactured cylinder head using AlSi10Mg with these rib structures was mounted on a 1.5l I3 GTDI engine bottom and tested on a dyno test bench under real conditions up to 170 kW. Same tests are carried out with a casted cylinder head for comparison. By adding the rib structures, the coolant temperature can be reduced by 38 K. This is a significant improvement. At the same time, a more homogeneous temperature distribution near the combustion chamber with a simultaneous reduction of the material temperature by 28 K is simulatively verified, leading to more efficient combustion and an increase in durability.

The second approach describes a general procedure. The results of this analysis can be transferred to other applications. Due to the comprehensive investigations of different structures, a suitable structure can be selected by means of weighted point evaluation. For the cylinder head, for example, NACA structures are selected for an area with low thermal loads. The main requirements in this case are manufacturability by LPBF and a low pressure drop.

It is shown that thermo-mechanically high loaded parts can be optimized exploiting the increased design freedom of LPBF. The studies are based on the example of a cylinder head but can also be applied to other applications where high cooling performance is required, such as electric drives or hydrogen combustion. ■