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FLUID FLOW-BASED TOPOLOGY OPTIMIZATION OF INTERNAL CHANNELS OF A LPBF-MANUFACTURED CALIBRATOR SIDE LATH

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Abstract. In this study, a method is presented to design embedded cooling channels in an additively manufactured metal part. A fluid flow-based Topology Optimization (TO) methodology was applied on a specific industrial case study with thermal objectives and constraints. The resulting design was 3D-printed and assessed numerically. In addition, the cooling efficiency is compared against that of the original design, which is machined. This work was performed using commercial software tools Simcenter STAR-CCM+ to perform the thermal and fluid flow optimization and simulations; NX to generate a final geometry from optimization results and 3DXpert to assess part printability.

1 INTRODUCTION

One key advantage of the Laser Powder Bed Fusion (LPBF) additive manufacturing process is the vast design freedom it allows. This geometrical flexibility grants more room for non-conventional design features that can improve the performance of the component or add extra functionalities otherwise not possible [1]. In this scope, Topology Optimization (TO) and LPBF can be considered to benefit from each other and work in tandem [2]. TO tools are commercially available and are often used to enable lightweight designs while satisfying certain mechanical constraints. However, the industrial use of TO involving fluid flow and thermal applications is yet scarce. Iterative design methods involving the use of Computational Fluid Dynamics (CFD), experimental work and/or experience are normally needed. These may not be the most adequate for parts that have more complex shapes [3].

A further challenge in the conception of TO applications is the back-to-CAD process of the TO-derived design suggestions. These TO results are normally available in formats which are generally not compatible with certain basic CAD operations or CFD simulation packages to perform a simulation to verify the part performance. This involves yet the need of extra effort before one can test a certain design idea.

Despite the abovementioned freedom of design that is inherent to LPBF, there are still manufacturing constraints that are to be taken into consideration when designing new applications. Hollow bodies, as those with embedded cooling channels are prone to be affected by manufacturability issues such as overheating and warping, due to internal overhang surfaces. The use of support structures can overcome this, but their removal is a complex process. Therefore, the proposed designs should comply with these limitations to achieve an efficient manufacturing process.

The combination of appropriate software tools allows a more desirable design process, where different constraint scenarios can be rapidly tested and 3D-printing files (e.g. STL) are generated without the need of too many loops in the workflow. This, combined with internal intricate cooling channels, can offer better and more efficient design approaches for fluid-thermal applications compared to for instance subtractive manufacturing.

In this paper, a printable geometry is derived with a fluid flow-based TO strategy applied to optimize heat transfer in a calibrator side lath, which is used in plastic extrusion processes to shape the polymer and cool it down. Section 2 includes the definition of the TO method and Section 3 provides some context on the calibrator side lath, analyzes the application of the optimization-simulation workflow and assesses the performance of the proposed geometry.

2 METHODS

The commercial Siemens-owned CFD solution Simcenter STAR-CCM+ [4] was used to perform the fluid flow-based TO analyses with its Adjoint Topology Optimization Model. This feature determines the optimal distribution of material within a design space and handles single objective optimization problems with constraints. Adjoint-based sensitivities are used to evolve a level set equation that determines the distribution of the solid/liquid material within the design zone. The material distribution is varied so that the objective is minimized. Once the TO analysis is converged, it is possible to extract the resulting material distribution and edit it further with Simcenter STAR-CCM+ or export it as an STL file.

The current setup allows several variables in the simulation to be defined as (weighed) objectives or as constraints. A common use that had been proven to work efficiently is to minimize pressure drop within a certain design space while keeping a certain fraction of solid/liquid material. For thermal applications, however, further magnitudes need to be considered. In the present work, the conjugate heat transfer model is used in the solid/design space interface to model the simultaneous coupled heat transfer between both regions.

Figure 1 includes a simple example where a design region is connected to an inlet and an outlet region where water is expected to flow at a certain inlet velocity and temperature that can be fixed. A solid region, subject to a fixed heat flux, is considered on the bottom. Two TO analyses were launched: a first one considering pressure drop as the objective function to be minimized; and a second one that minimizes the average temperature on the solid bottom wall. In these cases, inlet velocity and temperature were fixed as 1.92 m/s and 12°C, respectively. A 0.8 fixed fraction of solid material was introduced in both cases as a constraint. Heat flux was introduced as a function, as in Figure 4. Results display two different geometrical configurations of the solid/liquid interface and when thermal specifications are included, the suggested material distribution makes water flow as close as possible to the design space/solid interface, as could be expected. The average temperatures of the solid bottom wall are 130°C for the pressure drop-oriented case with a 2.1 kPa pressure drop, and 13°C for the temperature-oriented case with a 26.3 kPa pressure drop. Therefore, when adding a temperature objective function, the cooling efficiency of the resulting design was enhanced.

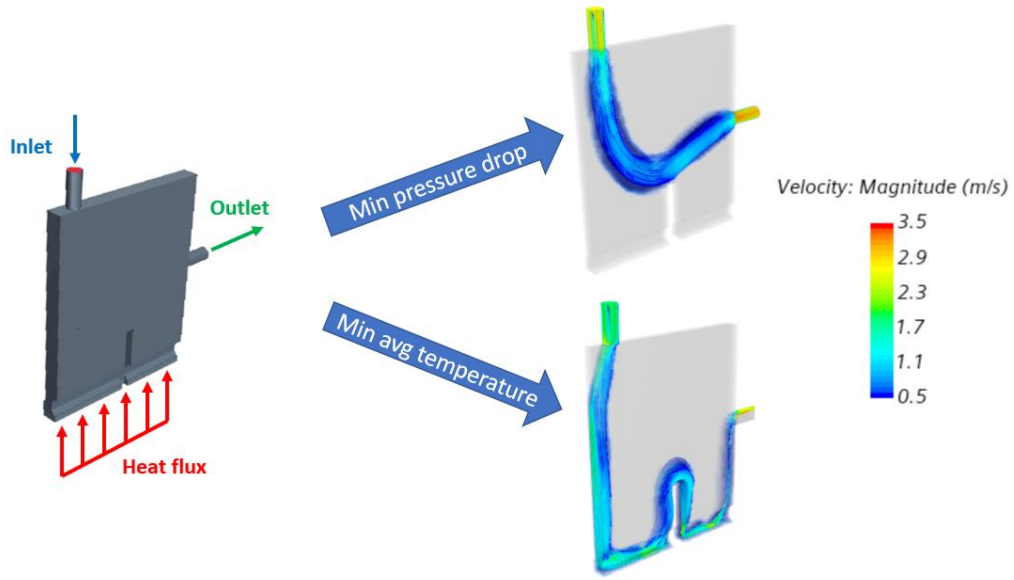

Figure 1. Resulting geometries after fluid flow-based topology optimization oriented to minimize pressure drop (top right) and to minimize the solid/warm wall interface temperature (bottom right).

3 INDUSTRIAL CASE STUDY

The fluid flow-based Topology Optimization methodology considering thermal objectives was applied on a calibrator side lath of an extrusion mold from Deceuninck. Simulations were performed to assess the efficiency of the TO-derived cooling channels. Printability of the resulting design has been evaluated.

3.1 Calibrator side lath

In PVC profile extrusion, after forming the plasticized material in its designated shape, the profile must be consolidated via a series of calibrators. These calibrators have the function of cooling the PVC from 185°C to 25°C while fixing the part in the final form. The efficiency of cooling is mainly dependent on the cooling channel geometry inside the calibrator. This efficiency also has a strong effect on the maximum line speed and final warpage of the product.

In the presented case study, the profile shown in Figure 2 is used. Here, cooling the inner chamber in contact with the traditionally designed calibrator piece is challenging as the calibrator part is in contact with a vast amount of PVC and has only very small cooling channels allowing only a small coolant flow. The second function, fixation of the profile, is performed via vacuum slots present in the calibrator. The vacuum slots are following the full contour of the calibrator in contact with the PVC material. These slots further constrain the position of the coolant openings.

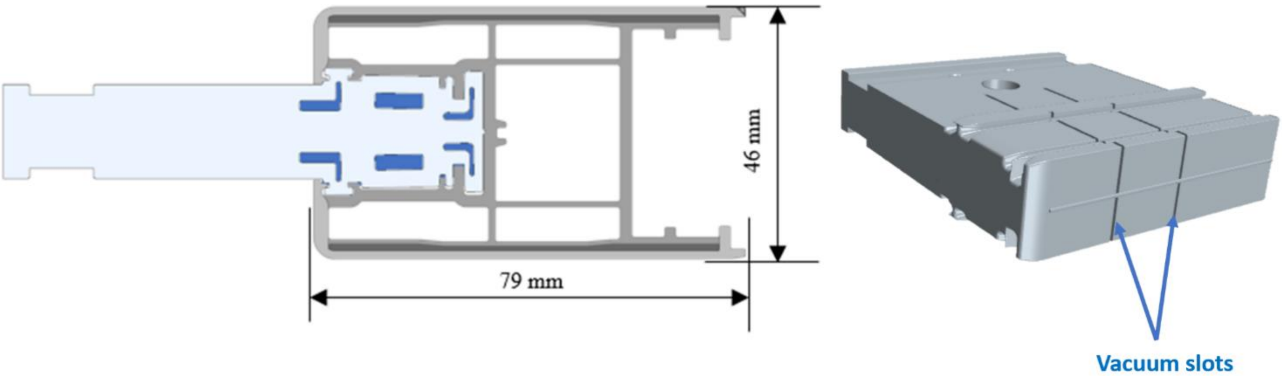

Figure 2. I-slide profile with traditionally designed calibrator side lath in light blue and cooling channels in dark blue (left) and 3D view of a section of the calibrator side lath (right).

Typically, DIN 1.2316 mold steel is used to produce calibrator parts as this material possesses good polishability, toughness, heat resistance and wear-resistant properties. It also offers a high corrosion resistance. This material is not readily available as LPBF feedstock and consequently, AMPO M789 tool steel from Böhler was used to cover the most important parameters: corrosion resistance and hardness. It has a chemical composition of 12.2w% Cr, 10w% Ni, 1 w% Mo, 1 w% Ti, 0.6w% Al, 0.5w% Si, <0.02w% C, Fe balance.

3.2 Topology optimization model and initial results

The calibrator side lath consists of a number of sections that are repeated and of a longer outlet section. A so-called “unit cell” of the calibrator side lath was considered in this study to enable rapid manufacturing of a prototype using a conventional LPBF machine. Thus, instead of 200 mm, its length was fixed to 80 mm by including one side lath section together with the inlet and outlet sections. The design space was created so that it covers all the regions in contact with the hot PVC and an offset of 1.1 mm in between the part outer surface and the closest cooling channel. This was made to avoid mechanical failure of the part during operation.

Cool water at 15°C was considered to flow along the design space with an inlet pressure of 3 bar, aligned with Deceuninck’s set-up. The PVC heat flux was modelled following a power function in the PVC flow direction that had been derived by Deceuninck in previous work. The realizable k-epsilon turbulence model and the coupled solver were used to define the fluid flow solution [4]. The conjugate heat transfer model was again applied in the interfaces. An adaptive mesh function in the design space was designed so that the mesh becomes finer in the solid liquid interface and coarsened elsewhere. The optimization objective function, as in previous example, was set as the average temperature of the solid/design space interface. A minimum solid fraction was set to 0.2 to allow enough space for channels, since the design space is particularly small.

The resulting material distribution is depicted in Figure 3. This resulting design can be exported in STL format and edited in the CAD software Siemens NX [5] as a convergent body to perform further Boolean operations, if necessary.

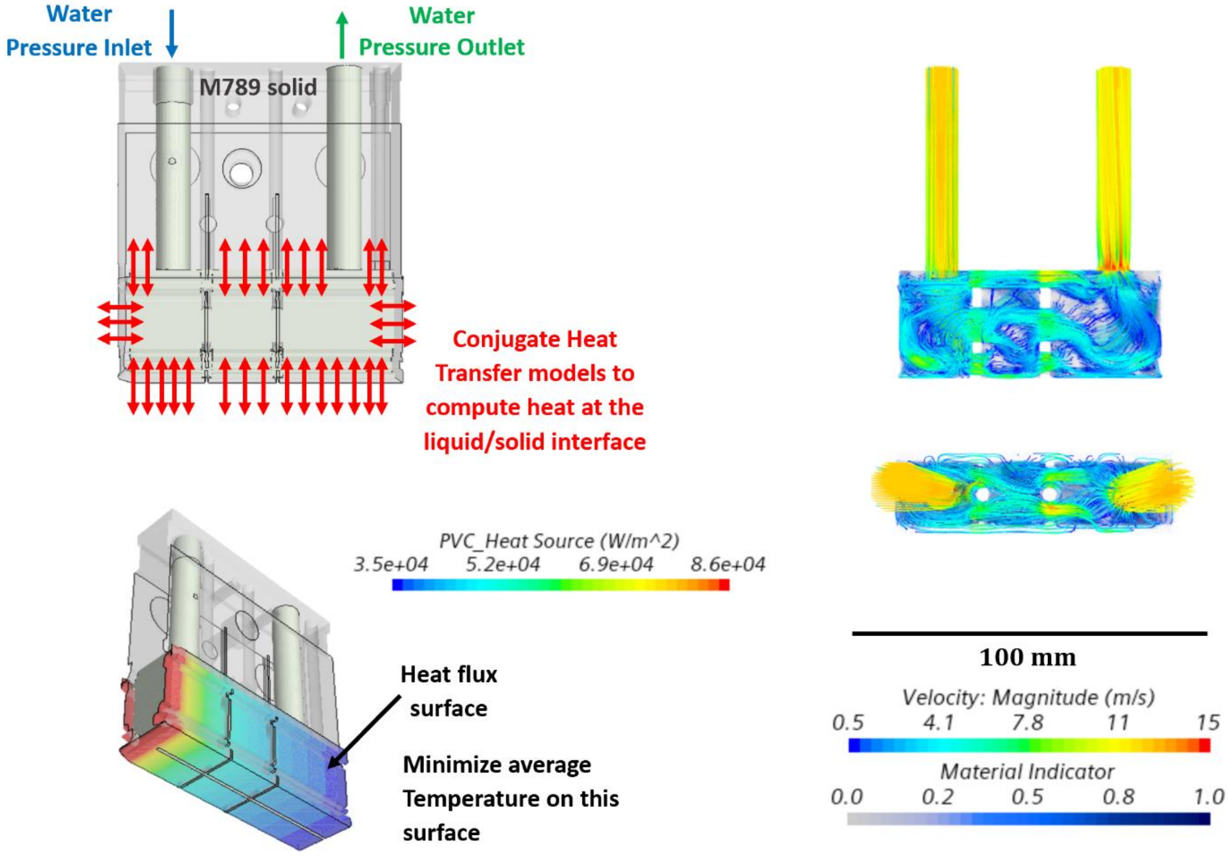

Figure 3. TO design space and boundary conditions (left) and suggested material distribution (right).

3.3 Design from separated streamlines

It was known, from previous experience with LPBF of M789, that individual cylindrical holes of up to 1.3 mm diameter can be printed with little risk of overheating or deformation issues that may make the manufacturing process fail.

Simcenter STAR-CCM+ allows to create flow streamlines during its post-process and to export them in STL files. These individual streamlines were obtained from the TO file and imported in NX, where individual channels of 1.3 mm diameter were generated, as depicted in Figure 4.

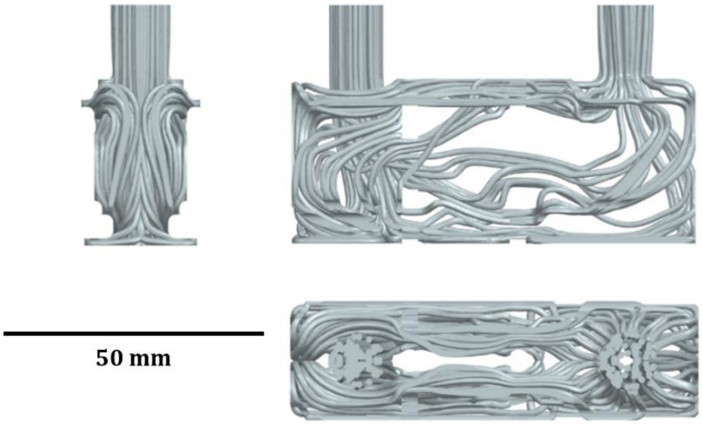

Figure 4. Streamline-derived design.

The manufacturability of the calibrator side lath was assessed with the help of Oqton's/3D Systems' AM software 3DXpert [6]. In general, one needs to avoid to have high failure risks due to internal features, where no supporting structures can be placed such as: (i) islands without connection to solid material underneath (ii) large downfacing surfaces (i.e., faces with only powder underneath and opposite to the Z direction) and (iii) sharp edges.

This assessment with 3DXpert displayed in Figure 5 show that, due to the smaller size of the channels (less than 5 mm in XY) in the streamline-derived design there is no need for support on overhanging downfacing surfaces. There are also minimal sharp edges due to the small size of the channels and its geometry. For these, since the feature is small, the risk of escalation into a major error is low. The reason is that there is enough material around these small features to dissipate heat and keep a high dimensional stability of the solid material.

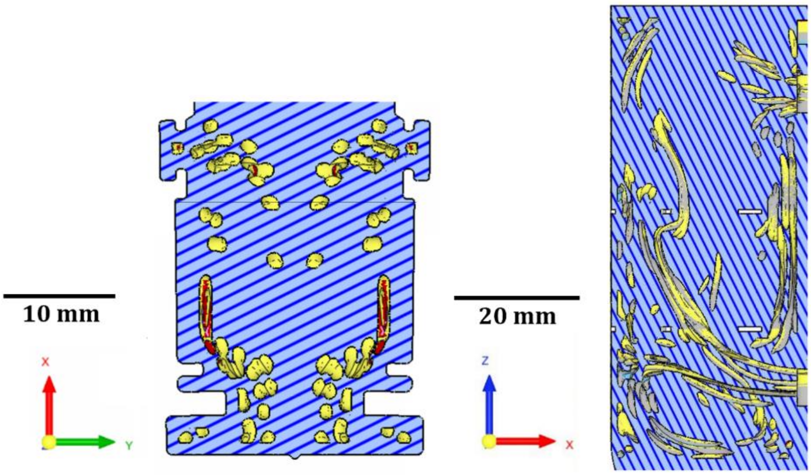

Figure 5. Cross section of streamline-based design with downfacing surfaces in red, (left) and no significant internal sharp edges (right).

The streamline-derived design specimens were fabricated at the Mechanical Engineering Department of KU Leuven in a ProX DMP 320B machine, equipped with a 500 W continuous wave fiber laser with a 90 µm laser spot diameter [7]. Böhler M789 AMPO powder with a particle size range D10-D90 of 20-50 µm was the employed raw material. All parts were produced with Certified M789 parameters for LT 60 µm, released by 3D Systems.

3.4 Comparison with original solution

The performance of the new calibrator design was compared with the original solution that was produced with Electrical Discharge Machining (EDM). To do this, the extracted heat $\dot{q}$ was calculated with the following expression:

$$\dot{Q} = \dot{m} \cdot \Delta T \cdot c_p \tag{1}$$

where $\dot{m}$ is the coolant (water) mass flow, ΔT is the outlet-inlet temperature difference of the coolant and c_p is the coolant specific heat capacity. The extracted heat was computed to be 620 W for the original design and 697 W for the proposed optimized channels. This increases its absorption capabilities by 12.42%.

Additionally, the maximal and average temperature on the solid/PVC interface were determined and used as a performance indicator. The average temperature were 55.1°C (original design) and 43.0°C (optimized channels), and the local maximal temperature were 23.5°C (original design) and 20.6°C (optimized). Therefore, the TO-derived solution presents a lower and more uniform temperature distribution, which is beneficial for the global plastic extrusion process. Temperature distributions are displayed in Figure 6.

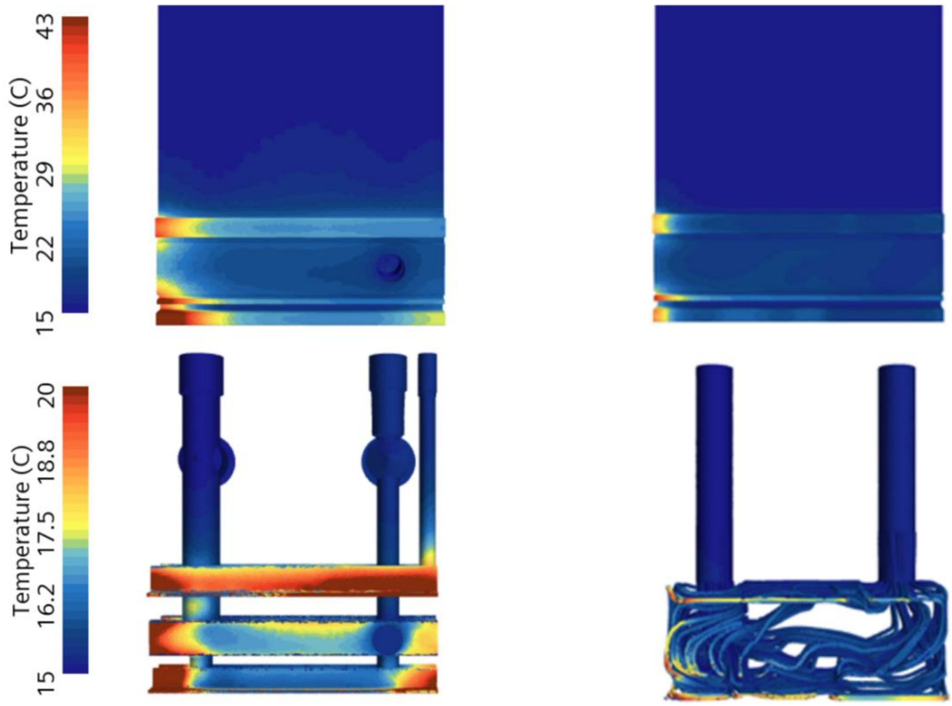

Figure 6. Solid (up) and water (down) temperature distributions for the original design (left) and TO-streamline-derived design (right).

4 CONCLUSIONS

This study proposes a methodology workflow to obtain designs that attain an enhanced cooling efficiency of critical parts in industry and can be manufactured with AM technologies. The Simcenter STAR-CCM+ adjoint-based TO tool was proven to deliver geometries that improve the thermal behavior of parts with embedded cooling channels. The results show that the extracted heat on an industrial case study increases significantly in comparison with an original solution manufactured with subtractive technologies. Moreover, using TO/CFD resulting velocity fields as design inputs with an efficient back-to-CAD process of the derived design ideas enable LPBF-manufacturing. The optimized geometry can be produced with an LPBF machine since the streamline-based design complies with the manufacturing constraints of the process. As future work, the presented approach could be adapted as to include manufacturing constraints directly in the TO process as to e.g. avoid overhangs, sharp edges or geometries prone to overheating during the LPBF process. Additional optimization parameters involving fluid flow such as pressure drop, coolant velocity or maximal temperatures could also be considered as either weighed objective functions or extra optimization constraints.

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