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Sinico, M.; Ranjan, Rajit; Moshiri, M.; Ayas, Can; Langelaar, Matthijs; Witvrouw, A.; van Keulen, Fred; Dewulf, W.

Publication date
2019

Document Version
Final published version

Published in
Solid Freeform Fabrication 2019

Citation (APA)
Sinico, M., Ranjan, R., Moshiri, M., Ayas, C., Langelaar, M., Witvrouw, A., van Keulen, F., & Dewulf, W. (2019). A mold insert case study on topology optimized design for additive manufacturing. In *Solid Freeform Fabrication 2019: Proceedings of the 30th Annual International Solid Freeform Fabrication Symposium - An Additive Manufacturing Conference* (pp. 1921-1931). University of Texas.

Solid Freeform Fabrication 2019: Proceedings of the 30th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference

A MOLD INSERT CASE STUDY
ON TOPOLOGY OPTIMIZED DESIGN FOR ADDITIVE MANUFACTURING

M. Sinico[1,2], R. Ranjan[3], M. Moshiri[4], C. Ayas[3],
M. Langelaar[3], A. Witvrouw[1,2], F. van Keulen[3], and W. Dewulf[1]

[1] Department of Mechanical Engineering, KU Leuven, 3001 Leuven, BE
[2] Member of Flanders Make - Core lab PMA-P, KU Leuven, 3001 Leuven, BE
[3] Precision and Microsystems Engineering, Delft University of Technology, 2628 CD Delft, NL
[4] Department of Mechanical Engineering, Technical University of Denmark, 2800 Kgs. Lyngby, DK

Abstract

The Additive Manufacturing (AM) of injection molding inserts has gained popularity during recent years primarily due to the reduced design-to-production time and form freedom offered by AM. In this paper, Topology Optimization (TO) is performed on a metallic mold insert which is to be produced by the Laser Powder Bed Fusion (LPBF) technique. First, a commercially available TO software is used, to minimize the mass of the component while ensuring adequate mechanical response under a prescribed loading condition. The commercial TO tool adopts geometry-based AM constraints and achieves a mass reduction of ~50 %. Furthermore, an in-house TO method has been developed which integrates a simplified AM process model within the standard TO algorithm for addressing the issue of local overheating during manufacturing. The two topology optimized designs are briefly compared, and the advantages of implementing manufacturing constraints into the TO algorithm are discussed.

Introduction

The integration of Additive Manufacturing (AM) in the supply chain of industries for tooling production is continuously growing and numerous studies highlight its benefits [1]. The reduced lead time, leading to lower overall manufacturing cost, and the exploitation of AM freedom for tooling design with the possibilities of optimization and customization are drivers for AM adoption.

Especially in the mold-making sector, the implementation of AM allows typically to either reduce costs for low-run injection molding and/or to increase value by redesigning mold cavities and inserts to reduce cycle time and increase part quality. The first is achieved more commonly by plastic mold inserts produced via e.g. material jetting or SLA (stereolithography), where wear resistance is no longer the most critical factor for the part [2,3]. The latter is becoming the key for the successful industrial acceptance of metal additively manufactured mold inserts, where techniques like LPBF enable to produce a near-net-shape component often optimized to reduce injection molding cycle time by the presence of conformal cooling channels.

The redesign of the cooling system and the implementation of conformal cooling channels to enhance the cooling efficiency of a mold is the most common example of AM design freedom in the injection molding sector and corresponding academic research [4,5,6]. Another benefit of conformal cooling channels is the improved thermal management of the mold, that reduces the defects, e.g. shrinkage, on the molded part [7]. However, to benefit further of the AM potential, the removal of excessive material that doesn't contribute to the mold overall performance should also be considered. This step is generally not performed because of poor knowledge of the AM design guidelines. One solution to eventually implement this is topology optimization.

Topology Optimization (TO) is a computational design tool which is used to find optimal material distribution for a predefined objective and a set of constraints [8]. E.g. one most common problem is to find a structure with maximum stiffness for given loads within a constrained volume. Typically, designs found using TO are geometrically intricate and, hence, difficult to manufacture using conventional techniques. However, enhanced design freedom allowed by AM enables realizing these designs. Therefore, it becomes easier to directly manufacture the free form designs and organic shapes suggested by TO methods.

Whereas TO hence has ample potential to be integrated in the design stage of mold and mold components that are to be fabricated by AM, few obstacles remain. The barrier of inadequate software tools with high training time and sometimes high computation time are nowadays being overtaken by the development of commercial user-friendly TO software [9] and more powerful computer hardware, respectively. Moreover, distinct limitations of the AM process itself have only recently started to be included in the TO algorithms. More specifically, after D. Brackett et al. in 2011 publicly recognized this need [10], AM considerations like build orientation, overhangs prevention and self-supporting designs have been first studied in academia [11,12,13], and subsequently implemented in some commercial software. However, the preceding described advancements are new and still in progress, and only a few TO case studies related to injection molding have been shared in literature [14,15,16], since the removal of excessive material is not considered the primary objective in this specific application.

In this work we want to demonstrate, through a metal mold insert case study, that the application of TO with additive manufacturing constraints can be beneficial for the value-chain of injection molding. Diminished use of material during fabrication and shortened AM production time are the main reasons for adoption and will lower the total cost of the part. In addition, including AM constraints directly in the TO step will ensure that the final designed part can be manufactured with reduced post-processing needs.

To achieve the goal, firstly a commercial TO tool [17] that already adopts AM constraints is used on the case study. In this tool, the AM constraints are purely geometrical and the definition of LPBF building direction along with maximum allowable overhanging angle must be added while setting the TO problem. However, geometrical AM constraints are based on purely empirical values that depend on the machine, process parameters and material in use, and do not address the underlying thermal aspect of the problem. Thus they do not guarantee avoidance of local heat accumulation or, on the other hand, they might be overly restrictive.

For this reason, a second in-house TO tool has been used which integrates a simplified thermal AM model within the TO loop. The method imposes an additional temperature constraint in the conventional TO process so that the resulting design is free from overheating. A 2D implementation of the method is presented in R. Ranjan et al. [18]. This case study is the first application of the novel TO scheme extended in a 3D domain. The advantages of implementing the physics of the LPBF process into the TO algorithm are discussed in the outlook section of this paper, briefly comparing the results from the two adopted approaches. But before that, the case study and problem formulation are presented in the next sections, respectively.

Initial case study design

The case study investigated in this work is a mold insert for the injection molding of ABS parts and has been provided by a manufacturer of consumer goods. The insert has to be produced via LPBF, with maraging steel grade 300 material. The design of the mold insert has already been partially optimized for AM, with a conformal cooling channel running beneath the mold cavities. The shape of the channel itself has also been redesigned to avoid the use of supports inside the channel during LPBF production. A general overview of the case study is shown in Figure 1.

In the design, mounting holes and centering holes are the main features devised for the assembly of the insert with the mold box and therefore will be critical features to consider for the optimization, together with the mold cavities and serving cold runners.

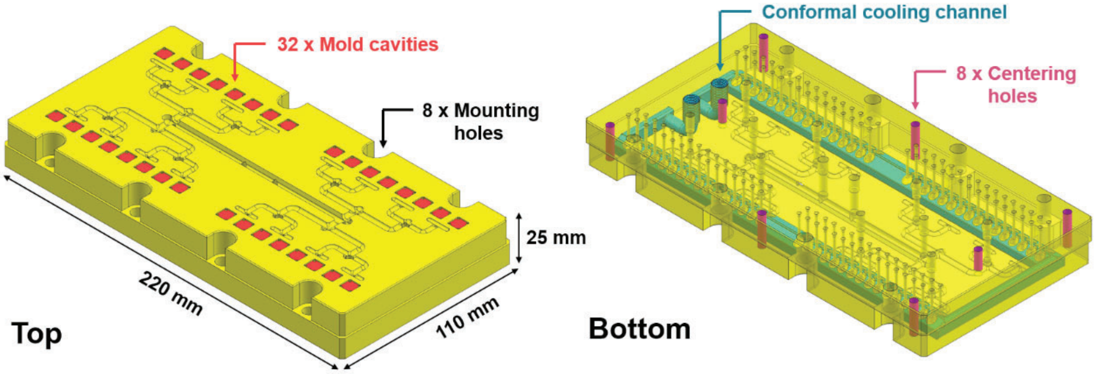


Figure 1. Original design of the injection molding insert.

Along with the initial design, the general injection molding parameters have also been provided by the manufacturer and are summarized in Table 1.

Table 1. Injection molding parameters, from the original mold insert manufacturer.

Material	Maraging 300 [19]
Volume of the insert	536603 mm^3
Mass of the insert	4.35 kg
Injection pressure	620 - 760 bar
Holding pressure	100 bar
Water pressure	3 - 6 bar
Clamping force	393 kN

Absolute theoretical density	8.1 g/cm^3
Young's modulus	186 GPa
Ultimate strength (as-built)	1230 ± 70 MPa (XY); 1220 ± 20 MPa (Z)
Yield strength Rp0.2% (as-build)	1080 ± 90 MPa (XY); 1090 ± 50 MPa (Z)
Thermal conductivity at 25 °C	20.9 W/(m*K)

The material properties, which are included in Table 1, are taken from the material datasheet of a large LPBF machine company [19] to simulate at best the material condition of the mold insert after AM production (as-build state).

Formulation of TO problem

The definition of the optimization constraints and loading conditions is one of the most critical steps in formulating a TO problem. It must be carefully done taking into account the actual case study functionality as well as limitations imposed by the TO tool that is going to be used.

Therefore, for this case study the design space where the TO solver can operate has been simplified to ease the computation time as well as to retain critical features (keep-in space) that shouldn't be modified by the TO software. Moreover, only a quarter of the original design has been considered for the optimization as the mold insert has almost perfect double symmetry. Design space and keep-in space are illustrated in Figure 2, in pink and yellow color respectively. Engineering assumptions together with inputs from the manufacturer have been combined to derive the actual keep-in features as well as their size. More specifically, mounting and centering holes, the design of the cavities, the runners and the conformal cooling channel have to be excluded from the design space. As a general rule, 2 mm of material has been kept for most of the keep-in features besides the mounting holes, where a 5 mm offset is advised. Figure 2 summarizes all the previous assumptions.

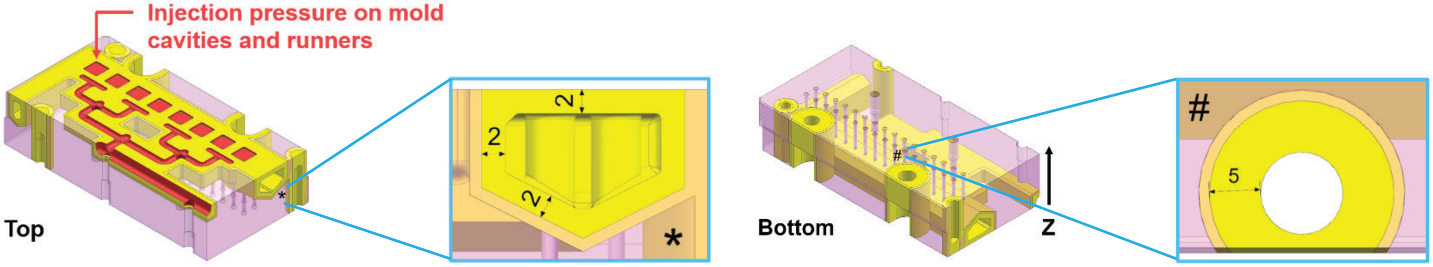
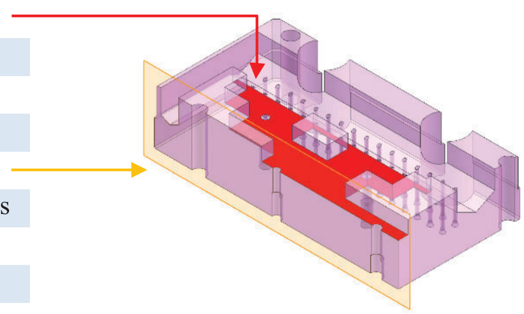


Figure 2. Design space and keep-in space (pink and yellow colors respectively) for the case study TO problem formulation, with zoomed in exemplifying keep-in features; Z is the AM building direction.

The loading condition tries to mimic the injection pressure load on the runners and mold cavities (Figure 2) using the maximum possible pressure (in Table 1) multiplied by a 1.5 safety factor. The water pressure in the channel is negligible being 3 orders of magnitude lower than the injection load. Additionally, the complicated runner design (shown in red in Figure 2) has been simplified to a planer design (shown in red in Table 2). The motivation behind this simplification is to facilitate meshing operation using structured grid, utilized by the in-house TO code. Although the commercial software can efficiently handle curved surfaces, planar loading surfaces are used for the commercial TO as well so that results from both TO tools can be compared later.

Table 2. Summary of TO loading conditions and constraints.

Injection pressure	760 * 1.5 (safety factor) bar
Water pressure	Negligible
Mounting holes	Fixed for all 6 degrees of freedom
Centering holes	Fixed for all 6 degrees of freedom
Additional design constraint	Planar symmetry constraint
Material properties	From [19], isotropic, as-built conditions
LPBF max overhang angle	45 degrees
LPBF building direction	Z ↑ (Figure 2)



Mounting holes and centering holes are set as fixed surfaces for all 6 degrees of freedom. Employed geometrical AM constraints are subjected to the AM building direction of the component (Figure 2) with the imposed maximum overhang angle of 45° commonly adopted in LPBF manufacturing. To conclude, a symmetry constraint as indicated in Table 2 is present to allow the resulting TO material to be distributed symmetrically in respect to the selected plane. All the results in this paper are shown for half of the mold insert original design. This means that we performed the TO on the quarter design and then used symmetry for creating half of the design which is shown in the result section.

Commercial TO software results

A first TO has been performed with a new commercial software [17] that already implements AM constraints in the optimization setup, like overhang prevention or self-supporting control. The main advantage of the selected tool is the capability to obtain a print-ready design after TO i.e. a STL file with high resolution of triangulation is obtained which can be manufactured without much post-processing efforts. The software is also quite computationally efficient and, for a global resolution [17] of e.g. ~6 mm (the set minimum feature size of the TO result), it can be executed in a modern i7-7820HQ | NVIDIA Quadro M1200 | 32 GB RAM workstation in less than 10 minutes for the selected case study.

The tool applies purely geometrical AM constraints, where building direction and a minimum overhang angle should be defined a priori. In this work, overhang prevention has been used, along with the material spreading option [17] set at 90 % to promote the creation of strut like structures. A simplified TO workflow is depicted in

Figure 3, where the removal of the overhangs can be observed for the case study after the application of the AM constraint. Loading conditions and fixed surfaces have been defined as described in the previous section.

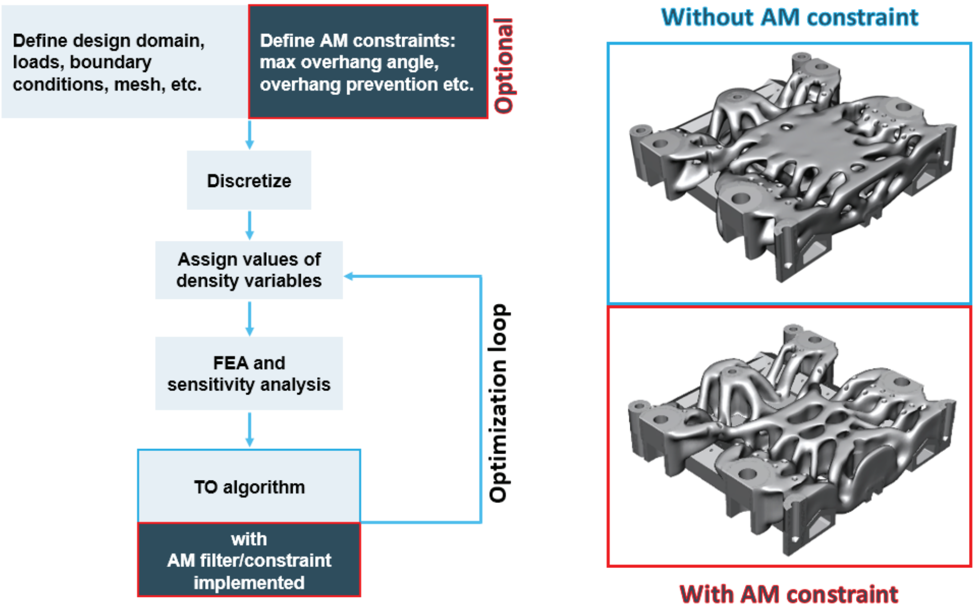


Figure 3. Simplified TO workflow of the commercial tool, with exemplifying AM geometrical constraint implemented (overhang prevention).

The optimization goal is to create the stiffest part for a given mass target, i.e. strain energy is minimized. Moreover, the maximum Von Mises stress and maximum displacement, calculated after the FEA step in the TO loop (Figure 3), should remain within prescribed boundaries to avoid stress concentration or inadmissible deformation of the insert while in operation. Therefore, a displacement < 130 µm is accepted after TO based on suggested values from available literature [20]. The optimization is subsequently run for different mass targets, and a summary of the results is plotted in Figure 4.

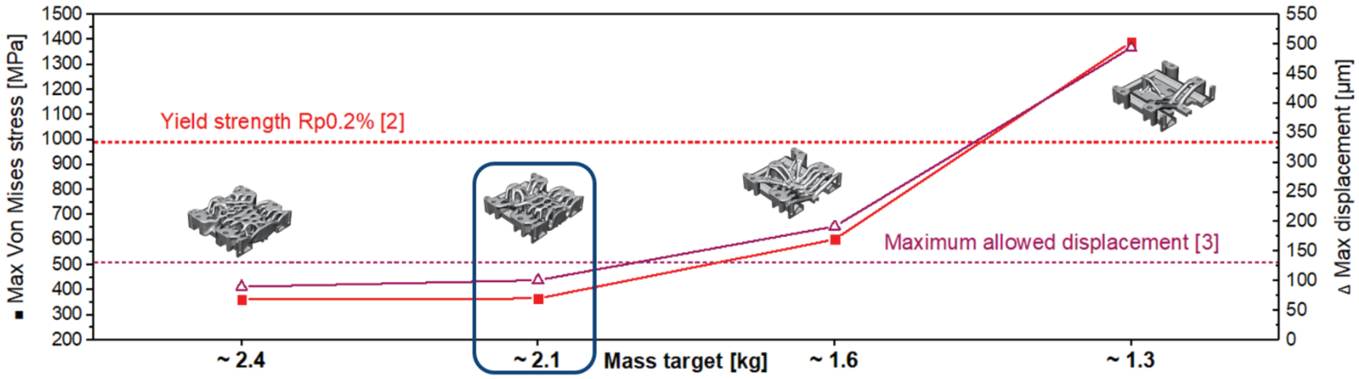


Figure 4. Calculated max Von Mises stress and max displacement for the optimized mold insert after TO at different mass targets.

Final minimum admissible mass is ~50 % after TO, while lower mass targets will increase the maximum displacement above the chosen threshold. A clearer view of the insert can be appreciated in Figure 5.

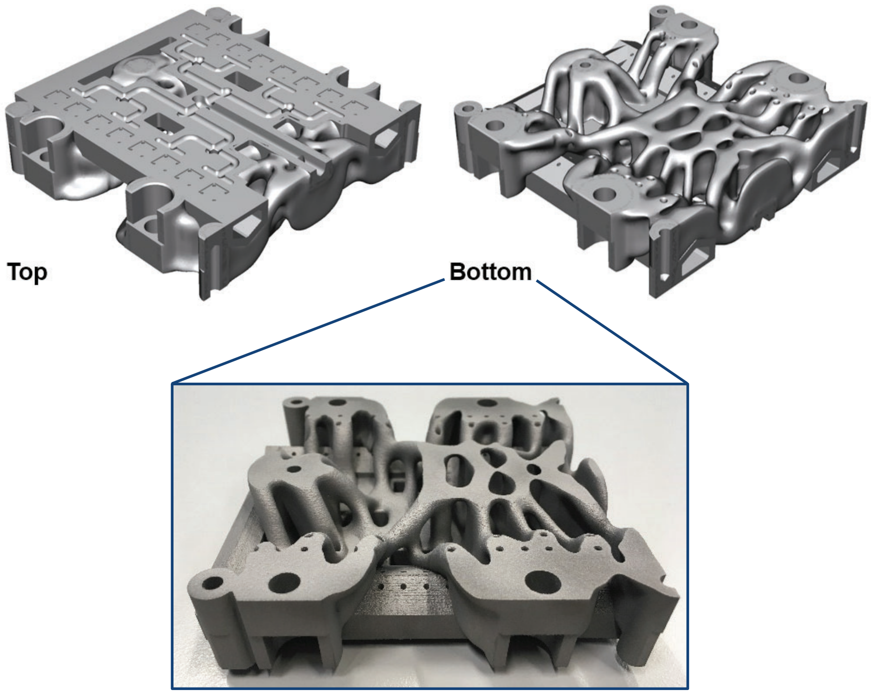


Figure 5. Topology optimized mold insert, commercial TO tool result with a LPBF produced showcase copy (bottom).

The material concentrates in the center to avoid the deflection of the runners subjected to the high pressure produced by the hot plastic coming from the injection molding machine nozzle, while anchoring at the fixed surfaces i.e. the mounting and centering holes. Color plots of the distribution of the stresses and the displacements after FEA have also been computed and are showed in Figure 6.

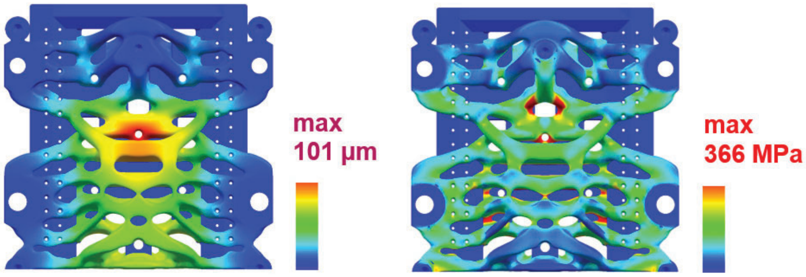


Figure 6. Color plots of the computed Von Mises stresses (right) and displacements (left) after FEA.

Finally, production time via LPBF is simulated with the parameters from [19] and a layer thickness of 30 µm in the 3DXpert 14.0SP2 software package [21]. The reduction in processing time is ~43 %, from ~23 hours of the original design to ~13 hours of the optimized insert, further evincing how the removal of excessive material via TO consequently decreases the AM manufacturing price.

In-house TO software results

The case study is also solved using an in-house MATLAB based TO algorithm. The code given by [22] has been extended to implement the conventional TO for solving compliance minimization problem with the same volume fraction as used for the commercial software. The resulting design is shown in Figure 7.

Next, the algorithm described in [18] is used for implementing hotspot based TO and the adapted design is presented. The novel method uses a simplified AM model in which a sequential steady-state thermal analysis is carried out for the purpose of detecting zones of heat accumulation referred to as 'hotspots'. The model is integrated with conventional density based TO with an additional constraint on hotspot temperature. The method of moving asymptotes, MMA [23] is used for optimization and sensitivities are computed using the adjoint method.

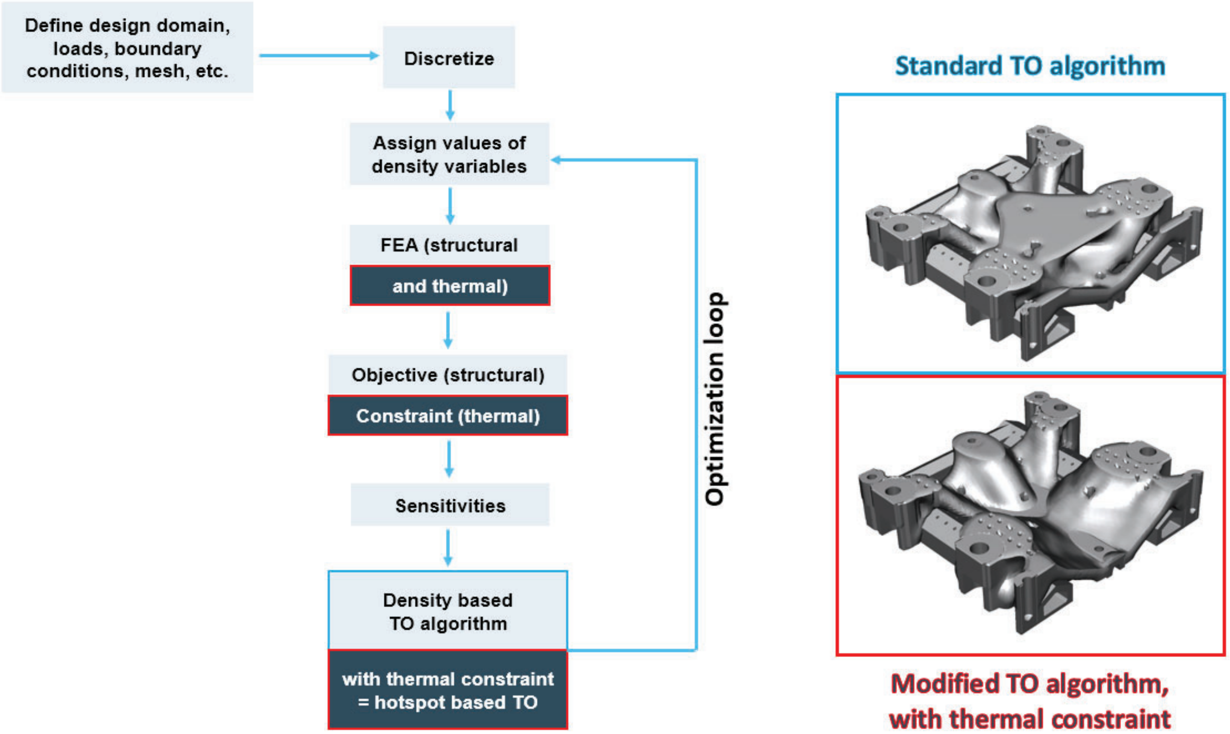


Figure 7. Topology optimized mold insert, with standard density-based TO tool result and in-house novel TO algorithm with AM thermal constraint (hotspot detection).

It should be noted, though, that the temperatures predicted using the simplified model are only indicative of heat accumulation behavior of the geometry being analyzed, and not real in-process temperatures. However, the deliberate choice of using a steady state analysis, instead of a detailed transient simulation, provides a computational advantage which enables integrating the model with TO. For further details on the algorithm refer to R. Ranjan et al. [18].

Outlook

In the considered case study, a significant reduction of ~50 % in mass and ~43 % in production time has been achieved with TO and these reductions have a direct implication on associated costs. This shows that the use of TO can assist designers in improving the efficiency of mold inserts by utilizing more complex geometrical features while lowering their mass and thus LPBF production cost.

Withal, as previously stated in this essay, performing topology optimizations without considering manufacturability constraints could yield more troubles than benefits, if the resulting design after TO cannot be successfully manufactured with the selected AM process. Thus, including AM constraints in the TO stage is fundamental and the choice of the correct constraints to be applied is still an open research discussion [13].

While the application of purely geometrical constraints in the TO algorithms has been proven effective and is nowadays implemented in commonly available commercial software, these TO methods do not address the underlying thermal aspect of the problem and thus do not guarantee avoidance of local overheating issues. If local overheating is present, defects such as dross and sag formation could appear on downfacing surfaces and thus decrease the obtained surface quality [24] or impose the use of supports to avoid build failure. More importantly, elevated temperatures during the build process has implication on microstructure evolution which in turn adversely effects physical properties.

The in-house developed software aims at tackling these issues by implementing a simplified AM model inside the TO loop. It essentially integrates a thermal constraint within the TO process such that zones of heat accumulation during AM fabrication are avoided. Although the in-house developed TO is one step closer to the physics of the actual AM process as compared to typically used TO methods which employ a geometrical constraint, the in-house algorithm still takes into account only the thermal aspect of LPBF. In practice, the LPBF process is an extremely complex phenomenon involving physics associated with fluid dynamics, heat transfer, structural mechanics, phase changes and interactions between them. Therefore, the found designs should be further analyzed before final printing. For example, a thermo-mechanical simulation of the AM process for fabricating these designs is foreseen as the immediate next step. Furthermore, the designs will be manufactured and metrological assessed for experimental validation. All these listed points of action are the subject of ongoing and future work.

The structural performances (compliance) of the designs obtained using the commercial tool and the in-house codes cannot be quantitatively compared, since the details about the TO algorithm used by the commercial tool are unknown. Nevertheless, a comparison from the point of view of local overheating can still be achieved by employing the same localized steady state thermal analysis developed for the in-house TO algorithm. The hotspot detection method [18] has been performed for all the topology optimized designs of the case study to compare the occurrence of heat accumulation. The results are portrayed in Figure 8.

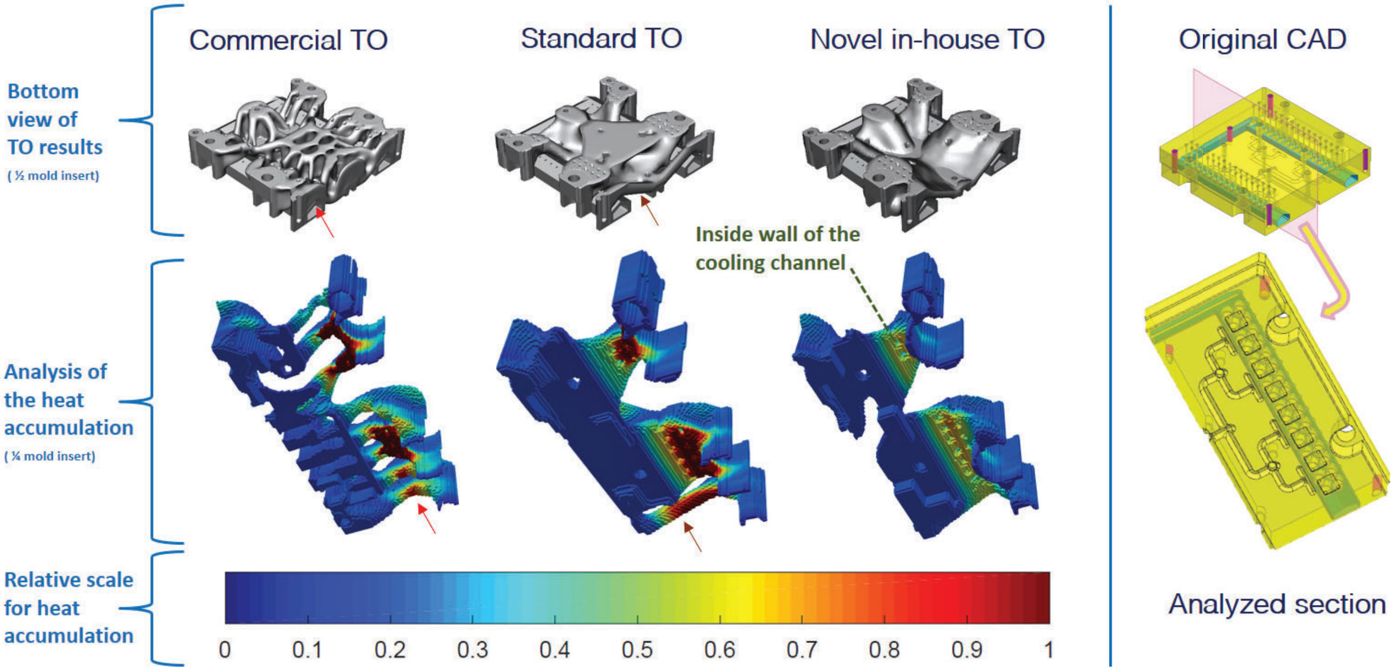


Figure 8. Obtained TO designs for the case study, with the analysis of the heat accumulation during LPBF manufacturing process; the localized steady-state analysis which is implemented in the novel in-house algorithm [18] has been used as a post-optimization step in order to compare the designs.

From the analysis, it is evinced how -looking at the common relative scale- the novel in-house TO tool with the thermal AM constraint limits the occurrence of heat accumulation both in down-facing regions of the optimized part and on the inside wall of the cooling channel. Consequently, for the same mass target, it is expected that an optimized design without local overheating can be printed with a greater geometrical accuracy and surface quality as compared to the other two designs in Figure 8. This hypothesis will need further corroboration by an experimental validation on the use case, as previously discussed.

The use of TO to reduce the overall mass of the component has still another indirect benefit. In the domain of design for AM and specifically in the design guidelines for part orientation on the build platform, the reduced mass unlocks the possibility to orient the insert in previous forbidden positions. This is due to the fact that residual stresses are dependent on the area of the exposed layer during LPBF, and bigger layers are more prone to have a larger maximum stress value [25]. Thus, a subdivision of the surface in smaller parts results in a lower stress value, which is exactly what is achieved with TO. As a consequence the insert, which was normally tilted to avoid large scanning areas per layer (Figure 9a), can be now oriented parallel to the build platform (Figure 9b).

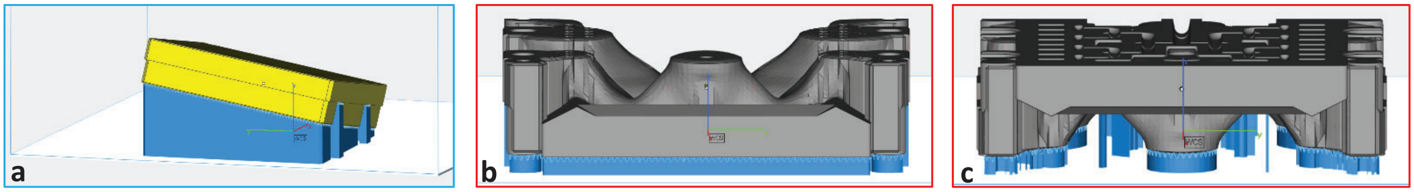


Figure 9. a) Example of the orientation of the original half-insert on the LPBF build platform, with supports (in blue); b) in-house TO design of the insert, with the considered building orientation (cavities face down); c) in-house TO design of the insert, alternative flipped orientation (cavities face up).

The orientation of the insert parallel to the build platform is advantageous for several reasons. Firstly, the reduced building height again contributes to the overall reduction of AM production time and hence production costs. Secondly, at the expense of placing some supports or computing again the TO with an inverted building direction (Figure 9c), tuned LPBF laser scanning strategies could be employed on the top surface of the mold to decrease the surface roughness and improve the surface quality. The top surface of the mold, where the mold cavities are present, is the most critical zone of the insert and several post-processing operations are performed to obtain a roughness value below 0.1 µm R_a. Rough-milling, grinding, semi-finishing plus finishing and a final EDM/polishing are all post-processes that increase fabrication time and cost. If even one of these operations could be avoided after LPBF, it would have a huge impact on the value chain of the product.

Normally, the insert is printed with the cavities surface face down, even if supports are present (Figure 9a-b) and therefore the surface quality is worse, since that surface will anyway undergo extensive and meticulous post-processing. However, the orientation presented in Figure 9c could be used to perform both remelting scanning strategies on the top surface [26] and/or in-machine laser polishing and laser ablation operations with novel LPBF equipment which has both a cw (continuous wave) and pulsed lasers. The latter is being developed at KU Leuven together with other members from the EU project PAM^2 (see acknowledgements), and initial results are shared in this same conference by J. Metelková et al. [27].

Conclusions

In this work, a metallic mold insert for the injection molding of ABS parts has been redesigned for AM employing different topology optimization algorithms. The aim was to reduce the overall mass of the component and hence save LPBF production time. Both a commercial software and an in-house developed TO algorithm have been used for the task. A reduction of ~50 % in mass of the part has been achieved for the analyzed TO setup and, accordingly, the simulated LPBF production time is decreased by ~43 %. However, while the commercial TO software employs geometrical AM manufacturability constraints, the in-house novel solution tries to tackle AM constraints by implementing a simplified AM model inside the TO loop. The underlying thermal aspect of LPBF fabrication is therefore included with a sequential localized steady-state thermal analysis and, thus, local overheating issues during manufacturing are avoided. An experimental validation of the optimization is foreseen and real LPBF parts are currently being produced and assessed to evaluate the surface quality on downfacing surfaces for the different optimized designs. Meanwhile, the developed thermal analysis, or 'hotspot indicator', has been employed to compare the obtained designs from both TO software. From the analysis, it is evinced how the novel in-house TO tool with the thermal AM constraint limits the occurrence of heat accumulation and, hence, the optimized design without local overheating could be printed with an expected greater geometrical accuracy and surface quality. In addition, the use of TO and the reduction of mass is theoretically advantageous to lower the amount of accumulated residual stresses. This means that the part can be conveniently printed in different orientations than the one empirically suggested for the original design. However, the proposed TO addresses only AM related thermal aspects using a simplified analysis and, therefore, found designs should be thoroughly analyzed using more detailed simulation tools before the final printing.

Acknowledgements

This research was funded by The EU Framework Programme for Research and Innovation - Horizon 2020 - Grant Agreement No 721383 within the PAM^2 (Precision Additive Metal Manufacturing) research project.

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