Improving the manufacturability of metal AM parts

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THERMAL CONSTRAINT IN TOPOLOGY OPTIMISATION

Numerous challenges of additive manufacturing (AM) are tackled in the European Horizon 2020 project PAM^2 by studying and linking every step of the AM process cycle. For example, PAM^2 researchers from the design, processing and application side have collaborated in this work to optimise the manufacturability of metal AM parts using an improved Topology Optimisation (TO) approach, including a thermal constraint. Additionally, the project is focusing on modelling, post-processing, in- and post-process quality control and industrial assessment of AM parts, with the aim of moving beyond the state-of-the-art of precision metal AM.

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Introduction

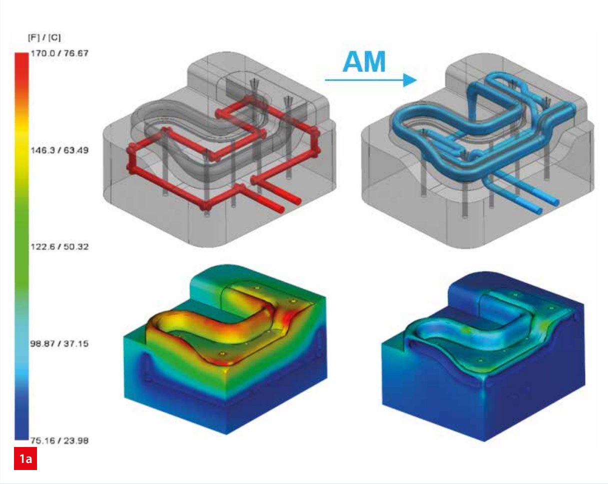
Additive manufacturing (AM) stands for a group of technologies where parts are built up layer by layer. AM has gained popularity during recent years primarily due to the reduced design-to-production time and the form freedom offered. However, several technological challenges still remain, such as a limited precision due to shrinkage, build-in stresses and dross formation at overhanging structures and a limited process stability and robustness. AM-printed parts often do not come out of the printer with the desired dimensions and shape.

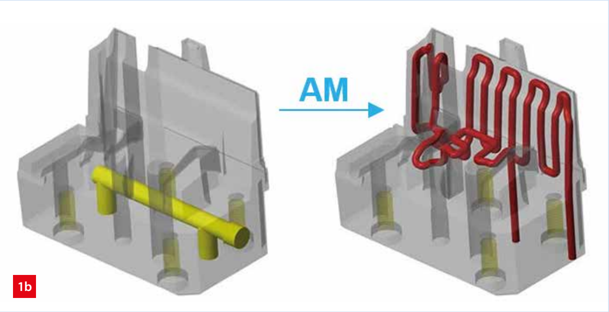
Therefore, we need to make sure that we design the parts and choose the printing direction and process in such a way that the manufacturability is optimised. In this work, a novel Topology Optimisation (TO) approach has been developed to enhance AM manufacturability and, as a result, to improve the final AM product. A case study of an injection mould insert illustrates this new Design-for-AM (DfAM) method. This work has been done within the PAM^2 consortium, where every step of the AM process cycle is studied. Therefore, links can be made between the initial design and the final result.

Improving manufacturability of AM parts

General concerns and common solutions

Improving the manufacturability of AM parts and ensuring that their desired dimensions, quality and surface finish are reached is a common theme in the PAM^2 project. Enhancing the precision of AM parts has direct implications for an industrial environment where the reduction of tolerances, a higher production output and a diminished need for post-processing are always desired. An industrial example is therefore presented in this work. By the use of novel TO techniques, developed within PAM^2, a metal mould insert for injection moulding has been redesigned for improved precision.





Two AM redesigns of the cooling system of mould inserts.
(a) Courtesy of Milacron (with heat transfer simulation).
(b) Courtesy of Renishaw.

AUTHORS' NOTE

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Injection mould inserts made by AM
Injection moulding is a method to obtain products by injecting molten plastic materials into a mould, and then cooling and solidifying them. When producing a mould using conventional manufacturing technologies, the starting material is a massive metal alloy part. This part undergoes many different processing steps before assuming its final shape. First, several cooling channels and ejector pin holes are drilled and plugged. Next, final finishing steps are performed to obtain the right surface quality and dimensional tolerances.

By using AM, a part that is already near-net-shape can be produced. Only the final finishing steps for obtaining a smooth surface are still required. Moreover, by employing DfAM, the design of the mould itself can be improved by, for example, defining a more efficient path for the conformal cooling channels that enhance the thermal management of the mould (see Figure 1), or by decreasing its weight while maintaining the same performance. Removing excessive material that doesn't contribute to the mould's overall performance has great benefits as it can drastically reduce the manufacturing time in the LPBF machine. This step is however often not performed because of poor knowledge of the AM design guidelines and because the removal of excessive material is not the primary objective in the specific application. One solution to implement this step is the use of TO.

Case study: Injection mould insert

Topology optimisation was performed on a metallic mould insert which is to be produced by LPBF of maraging steel 300 material. The case study, to be employed for the injection moulding of ABS parts, has been provided by a large manufacturer of consumer goods. The design of the mould insert had already been partially optimised for AM, with a simple conformal cooling channel running beneath the mould cavities (Figure 2). The reduction of weight, for the purpose of reducing LPBF production time and material use, however had not yet been considered in the design stage. TO was therefore selected as an optimal solution to perform this last step before the fabrication of the insert.

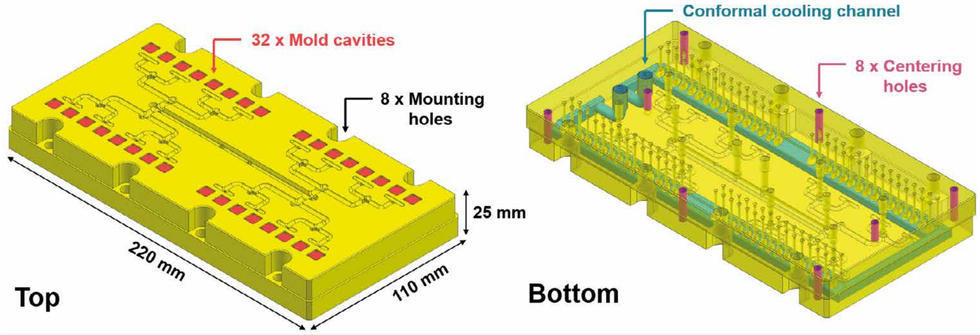
PAM^2 consortium

PAM^2, which stands for Precision Additive Metal Manufacturing, is a European Horizon 2020 MSCA project in which six academic and six industrial participants collaborate on improving the precision of metal AM. PAM^2 started in December 2016 and will run till the end of November 2020. The specific metal AM technology studied here is LPBF (laser powder bed fusion), where successive layers of powder are molten selectively by a laser to form the 3D AM part.
Research is done for each process stage of AM, going from the design stage to modelling, fabrication, measurements and assessment. For each step the aim is to progress the state-of-the-art with the goal of improving the final AM part precision and quality by implementing good precision engineering practice.

The overall objective of PAM^2 is to ensure the availability of high-precision AM processes and (computational) design procedures. Detailed objectives are:

1. to develop advanced (computational) design tools, enabling competitive designs, better use of AM possibilities against minimal design costs, and reduced time-to-market;
2. to develop better modelling tools for first-time-right processing;
3. to optimise selective laser melting process strategies for improved part precision and feature accuracy;
4. to understand the link between post-process metrology and in-process observations, creating the basis for in-process quality control and process stability;
5. to develop innovative in-process and post-process techniques to reduce or remove roughness, porosity and internal stresses and to improve dimensional accuracy and mechanical properties.

PAM^2 researchers from the design, modelling, (post-)processing, metrology and application side are encouraged to form collaborations across the different process stages and to continuously interact with each other. Moreover, the developed research is tested on common relevant industrial end-user parts. Successful examples of such collaborations are the theoretical prediction and experimental validation of keyhole porosities [1], prediction of post-anneal AM microstructures [2], a novel benchmark part allowing the comparison of different AM machines [3], improvement of as-printed downward-facing surfaces [4, 5], and the development of novel in-process and post-process measurement methods [6, 7].
Besides ensuring that you get what you want, PAM^2 also aims to push the limits in terms of precision. As a result, low surface roughness [8, 9], reduced edge effects [10] and high-precision CT techniques [11] are obtained.



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Original design of the injection moulding insert.

Topology Optimisation

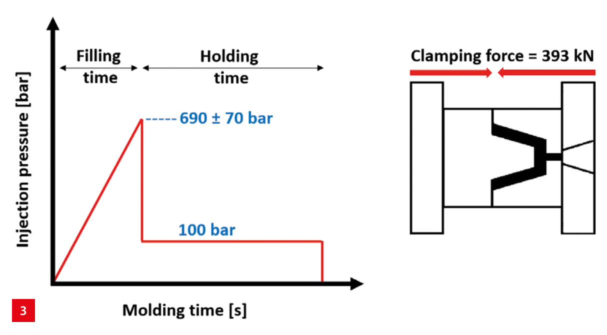
TO is a computational design tool which is used to find the optimal material distribution for a predefined objective and a set of constraints. One commonly solved TO problem is to find the optimal material layout such that the final design has maximum stiffness against a given set of loads for a prescribed maximum allowable volume. This is commonly referred to as a compliance minimisation or a stiffness maximisation problem in literature [12]. Designs found using TO are typically geometrically intricate and hence difficult to manufacture using conventional manufacturing techniques. However, the enhanced design freedom allowed by AM makes it possible to realise these designs. TO allows, on the other hand, for a proper exploration of the vast design space and it assists designers in finding optimal topologies.

This mutually benefitting relationship between TO and AM is very well recognised and a number of researchers have focused on integrating AM constraints within the TO algorithm. One commonly investigated AM constraint is that of overhangs or downward-facing surfaces. It is well-known that overhanging features are difficult to manufacture by AM. Multiple TO methods are therefore proposed such that resulting designs avoid overhanging features, thus enhancing precision in AM parts [13, 14]. This trend of addressing AM constraints within the TO method is, besides being a topic of research, also starting to find its way into commercial CAD packages.

For this specific case study, first a standard density-based TO was used to minimise the mass of the component while ensuring adequate mechanical response under a prescribed loading condition [15]. With this method no consideration was given to AM-specific constraints. Next, commercially available TO software [16] with geometry-based AM constraints was used to achieve a similar mass reduction.

Finally, an in-house TO method that was developed in the PAM^2 consortium [17] was utilised. This method tries to determine local overheating, or 'hotspots', during LPBF manufacturing via a simplified AM process model included in the standard TO algorithm. The aim was to create a TO-optimised design in which the above-mentioned hotspots are avoided. All three TO-optimised designs are briefly compared, and the advantages of implementing manufacturing constraints into the TO algorithm are discussed.

Initial case study design and requirements



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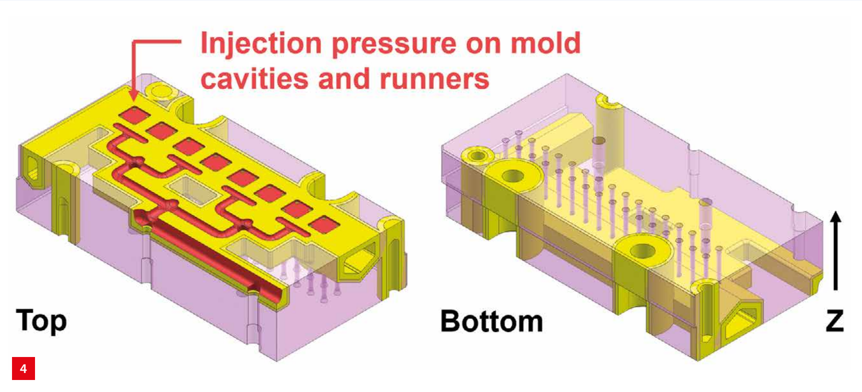
General injection moulding parameters for the examined case study.

All mould inserts need to possess some minimum requirements given by the process. To withstand the injection moulding process, the mould needs to be stiff enough not to deform during the injection cycle, it needs to be chemically inert not to react with the plastic, and, if possible, it should be made of a corrosion-resistant material considering that usually the cooling medium is water. Moulds also need to be very resistant to fatigue to ensure long life during multiple temperature cycles.

The exact degree to which each of the above-mentioned requirements are satisfied depends on the mechanical properties and the viscosity of the plastic material that is processed and on the injection moulding machine itself (e.g. the number of moulded parts that are to be produced per shot). The general injection moulding parameters for the case study have been provided by the manufacturer (see Figure 3). The mould insert material of choice was maraging steel 300, which is known for its superior strength and toughness without loss of ductility. This steel is also easily heat-treatable, and a simple age-hardening will confer excellent hardness and strength with good wear resistance.

TO set-up

The formulation of the optimisation constraints and loading conditions is one of the most critical steps in a TO problem. The actual case study functionality, as well as limitations imposed by the TO tool used, need to be taken into account. Moreover, the design space in which the TO code can



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Design space (pink) and keep-in space (yellow) for the case study TO problem formulation; Z is the AM building direction.

operate should be simplified as much as possible to reduce computation time, while maintaining the critical features that shouldn't be reshaped by the TO algorithm.

For this reason and in view of the almost perfect double symmetry of the case study, the TO was set up to consider only one quarter (comprising eight cavities) of the original mould insert. Moreover, features like the mounting holes, the centring holes, the mould cavities and runners plus the cooling channel (keep-in features in Figure 4, yellow colour) have been excluded from the TO design space and were not modified during the optimisation. The design space, in pink, was the volume where the TO could optimise the material layout for the given set of loads, boundary conditions and constraints, with the target of maximising the performance of the system.

The loading condition tried to mimic the injection pressure load on the runners and mould cavities using the maximum possible pressure (760 bar, Figure 3) multiplied by a 1.5 safety factor. The water pressure in the channel was considered to be negligible. Mounting holes and centring holes were set as fixed surfaces for all six degrees of freedom. The mechanical properties of the maraging steel 300 were acquired from [18].

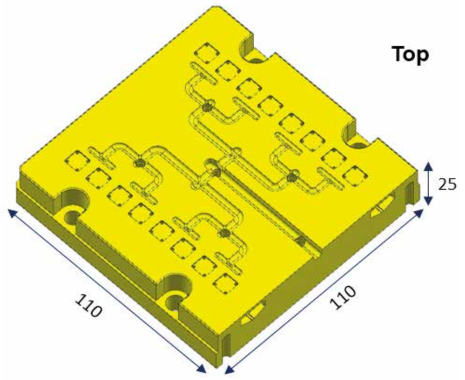
Figure 5a shows the original half mould insert and Figure 5b shows the optimised design obtained from a standard density-based TO [15]. For the latter no AM constraints were implemented and manufacturability might therefore be at risk.

Commercial platform

To improve manufacturability of the mould insert, TO has first been performed with commercial software [16] that already implements AM constraints in the optimisation set-up, like overhang prevention or self-supporting control. The tool applied purely geometrical AM constraints, where the building direction (Z in Figure 4) and a minimum overhang angle of 45° [19] should be defined a priori.

The optimisation goal was to create the stiffest part for a given mass target, i.e. the strain energy was minimised. Moreover, the maximum Von Mises stress and maximum displacement, calculated after the finite-element analysis (FEA) step in the TO algorithm, should remain within prescribed boundaries to avoid stress concentration or inadmissible deformation of the insert while in operation. A displacement < 130 μm was considered acceptable based on suggested values from available literature [20].

For the implemented loading conditions and constraints, a reduction of ~50% in mass was obtained (Figure 5c), from the original weight of 4.3 kg to a weight of ~2.1 kg after TO.



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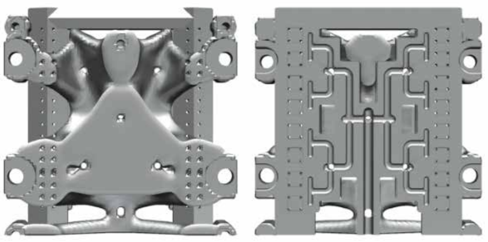

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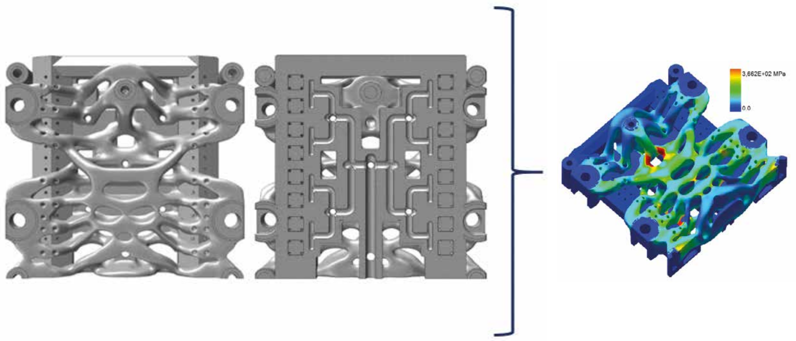

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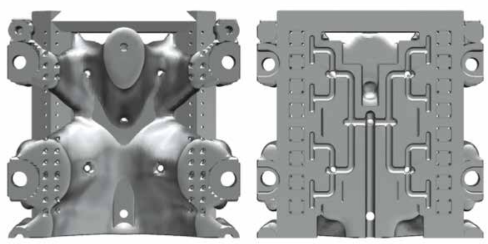
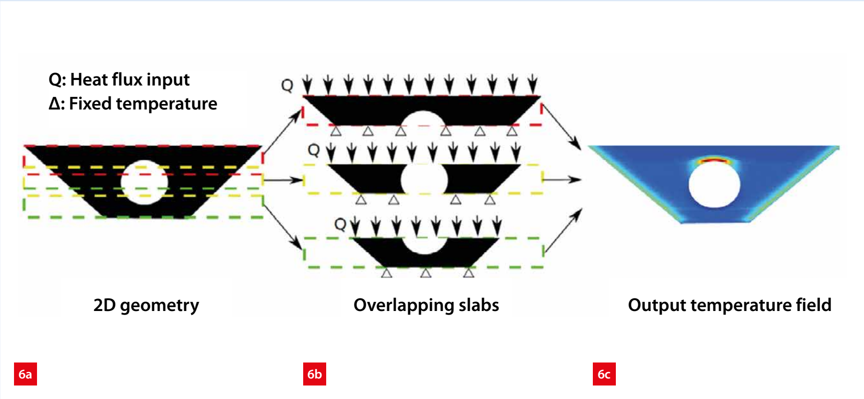


5d

Original design of a mould insert half (the TO design space being half of this) and optimised designs (each showing bottom (left) and top view).
(a) Original half mould insert design.
(b) Optimised design obtained from a standard density-based TO algorithm.
(c) Optimised design from the commercial TO software which adopts geometrical AM constraints, with on the right the corresponding Von Mises stress distribution (bottom view).
(d) Optimised design from the novel in-house heat accumulation TO method.



Hotspot detection method [17].
(a) A wedge-shaped geometry (example) decomposed into a set of overlapping slabs.
(b) Individual slabs with applied boundary conditions.
(c) Temperature field obtained by aggregating temperature information from all the slabs.

The maximum stress was 366 MPa, well below the yield stress of the employed material, while the corresponding maximum calculated deformation was 101 μm.

Novel in-house developed TO method

Within PAM^2 a novel TO method [17], which addresses the issue of AM-associated local overheating within the standard TO algorithm, was developed. First a simplified model of the AM process, which emulates the layer-by-layer heat addition and identifies zones of local heat accumulation in a given design, was created (see Figure 6 for a 2D case). Localised steady-state thermal analysis was used for this model as it offered significant computational gain, making it possible to integrate the model within the TO method.

The obtained temperatures were, because of this simplification, only indicative and hence not equal to the actual in-process values. However, it was found that this simplified model could rightly identify the heat accumulation locations. Hence, the model has been implemented as an additional constraint within a density-based TO method, while sensitivities were calculated using the adjoint method. The method of moving asymptotes (MMA) [21] has been used for the optimisation. Figure 5d shows the design obtained using this TO method with thermal constraint.

All three results (Figure 5b, 5c and 5d) were topology-optimised adopting the same set of load conditions and fixing constraints and having the same mass target (reduction of ~50% in mass). It was however expected that the manufacturability would improve by taking AM constraints into account (both 5c and 5d) and that an AM constraint based on the identification of local overheating (Figure 5d) was more desirable than a purely geometrical AM constraint (Figure 5c). This is studied in the next paragraph.

Results

The goals of this study were twofold:

1. To demonstrate how the implementation of TO in the design stage of a mould insert could be useful to decrease the total mass of the part, consequently reducing LPBF production time and hence costs.
2. To show how the implementation of a local overheating filter in the TO could improve the manufacturability of an AM part.

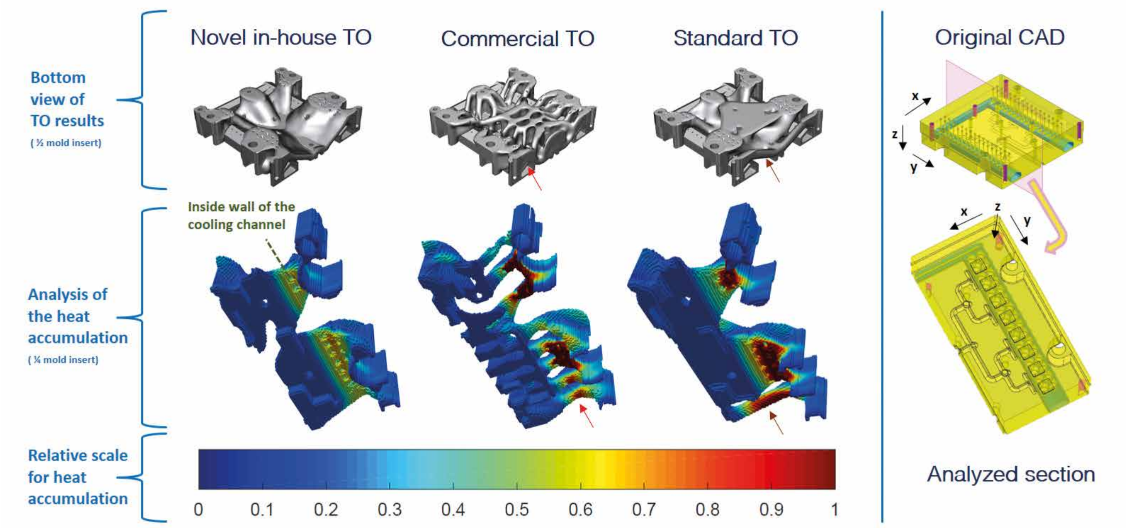
For the case study a reduction of ~50% in mass of the part was already achieved by standard TO (Figure 5b). Accordingly, the simulated LPBF production time was decreased by ~43%, from ~23 hours for the original design to ~13 hours for the optimised insert (fabrication parameters from [18]). However, performing TO without considering manufacturability constraints could result in a design that cannot be successfully manufactured with the AM process selected.

Commonly available commercial TO software does not guarantee avoidance of local overheating issues. If local overheating is present, defects such as dross and sag formation could still appear on downward-facing surfaces and thus decrease the obtained surface quality or impose the use of supports to avoid build failure. Including AM constraints in the TO stage is therefore fundamental and the choice of the correct constraints to be applied is still an open research discussion.

To prove that local overheating can still be present with purely geometrical AM constraints, a comparison with the hotspot detection method [17] was performed for all three optimised designs of the case study (Figure 5b-d). The resulting temperature field plots are reported in Figure 7.

It is clear, looking at the relative scale, how the novel in-house TO tool with the thermal AM constraints avoids or limits the occurrence of heat accumulation both in downward-facing regions of the optimised part and on the inside wall of the cooling channel. Consequently, for the same mass target, it is expected that an optimised design without local overheating can be printed with a greater geometrical accuracy and surface quality as compared to the other two designs in Figure 7.

At the same time, it must be disclosed that for the in-house TO design possibly higher deformations (> 130 μm displacement) during operation could occur, given the different distribution of the material in the design space. Therefore, more extensive FEA examinations should be performed on all the TO designs to evaluate the compliance with respect to the acceptable maximum stresses and deformations.



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Obtained TO designs for the case study, with the analysis of the heat accumulation during LPBF manufacturing performed with the PAM² novel in-house TO tool.

Discussion

Using TO for AM is extremely important since it allows to employ all unique capabilities of this manufacturing technology. TO is already often used for lightweight applications such as those encountered in aerospace. The mould insert example studied here shows that it is also very beneficial to use TO for tooling aplications. Care should however be taken to avoid overheating during the AM process. Such AM-safe designs can be made by using a TO algorithm with an integrated thermal model, which was developed within the PAM² project. The thermal analysis confirms that overheating is indeed avoided by using this novel TO method.

Future outlook

While thermal simulations already show the benefit of using the TO tool with integrated thermal model, an experimental validation is also planned within the PAM² scope. The unique concept of linking researchers from the different parts of the AM process cycle (from design to assessment and back) within PAM² makes this kind of validation feasible. Many more such cross-discipline results are expected before the end of the project in November 2020.

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