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Thermo-Elastic Topology Optimization For High Temperatures Gradients Using Load Separation

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Abstract

Designing components for thermo-mechanical loads is a challenging process. While mechanical loads like forces or pressure demand a stiff and thick-walled design, thermal loads create temperature gradients, resulting in thermo-mechanical stress from the structure's temperature proportional and, therefore, uneven expansion. In contrast to a pure mechanical load case, an initial design before optimization can already include stress levels beyond the limit of the material. Therefore, common optimization approaches for a preliminary design use exemplary systems with low-temperature gradients, so thermal stresses do not exceed the limit. From there, energy density is used to calculate the topology optimizations sensitivity and therefore decide which elements to remove and which to keep. This paper describes a novel approach for reducing thermo-mechanical stress by following the stress corresponding temperature gradients from the heat source to the sink to calculate a new sensitivity that helps to grow cooling channels. The optimization is exemplarily shown on a piston for internal combustion engines. While handling delta temperatures of 600K, results show a reduction in thermo-mechanical stress while reducing the component's mass. Because the approach reduces critical stress in a component, it allows the initial design (before the topology optimization) to have stress levels way above yield strength.

Keywords: Finite Element Analysis (FEA); topology; optimization; thermal; elastic; cooling; piston; stress; separation; temperature; gradients; structural; design

1. Introduction

The initial design of components in combustion engines such as engines, aircraft- and gas turbines, or rocket engines is a complex and, since the 1950s, heavily researched task [1, 2]. Generally, high surface temperatures are desirable. However, they weaken the material. In addition, uneven temperature distributions and, thus, different regions' expansions lead to high thermal stresses [1]. An increase in pressure accompanies the heat generation in the vicinity of the components. For the components, this means an additional mechanical load. The structure is, therefore, bearing and creating stress. The usual approach for thermal strain is to allocate gaps for expansion [2]. However, this clearance can reduce load-carrying capacity. The design of proper cooling channels under mechanical loads can also be challenging with 3D free-form geometries and uneven heat transfer. This paper introduces an approach to analyze a structure accordingly and use the gathered information to create an efficient overall design, including cooling channels. The process dramatically reduces the necessary experience in structural design and helps to digitize the design process.

2. State of the art

When designing for mechanical loads, increasing the wall thickness or simply filling the whole design space with structure is a viable initial design because it will at least withstand the loads (or more design space is needed). On the other hand, thermo-mechanically loaded components suffer from temperature-induced expansion, which

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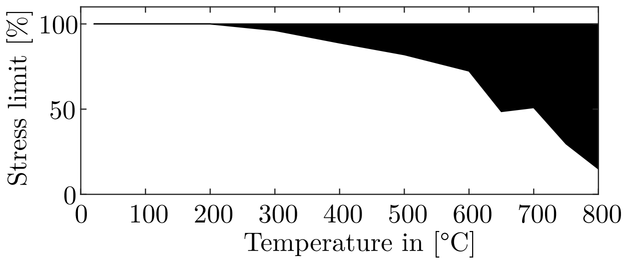

Fig. 1. Material Property: Reduction of stress limit over temperature of a nickel-base alloy normalized for room temperature 20 °C

can cause exceedingly high stress [1]. This stress is structurally born, and therefore thick walled designs, in general, produce higher stress. An initial design with stress below the material limit is not trivial [1, 3, 4]. The primary strategy for designing these structures was to accommodate thermal expansion [2]. In 2009 Haney et al. researched engine exhaust-washed structures with a temperature of 373 K. Haney et al. and Deaton et al. stated that at the time, traditional topology optimization methods like Rational Approximation of Material Properties (RAMP) could not produce acceptable results [2, 3]. Haney et al., therefore, developed a method to replace the thermal load with a mechanical phantom load corresponding to the forces created by the deformation of the to-be-optimized component. With this modulation, they could optimize for a mechanical instead of a thermal load. Deaton et al. built on this idea and replaced the thermal expansion with the reaction forces found in the thermal simulation. He and Haney used homogeneous temperature fields for their approaches [3]. Li et al. started using RAMP optimization for homogeneous temperature fields on 2D Problems. As a result, he created optimized structures for various applications with a delta Temperature of 10 K [5]. In 2010 Gao et al. proposed a method to enable RAMP optimization for thermo-elastic components with a temperature gradient by modifying the sensitivity. He optimized structures with a temperature difference of 6 K [4] with this method. 2021 Meng et al. improved the optimization further by including stress and temperature-based design utilizing the RAMP strategy again with a low-temperature difference of 10 K and relatively small heat flows of 0.335 W over 50 mm [6] Kanbur et al. described a method for parameter optimization to design cooling channels for injection molding. They modified the distance between the surface of the injection mold and the cooling channel to get a homogeneous cooling of the mold. Stress and more elaborated shapes were not analyzed [7].
Li et al. proposed a multi stage methode to design a heat-exchanger for electronics with a two-step generative process. Stresses were not involved [8]. The presented methods for optimizing thermo-elastic components treat thermal problems like mechanical systems by removing material where low stress or compliance occurs. This strategy is presumably the reason why negligible temperature differences were chosen as an example for topology optimization. Here a method is presented to design thermo-elastic components using topology optimization for high-temperature differences by focusing on the cause of stress in a structure. The method is presented in chapter 4 and applied to a piston for internal combustion engines in chapter 5.

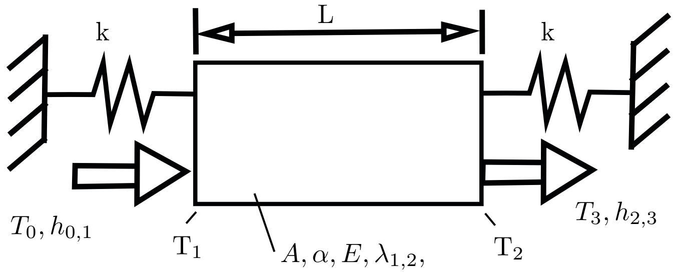

Fig. 2. Simplified model of thermo-mechanical stress mechanism

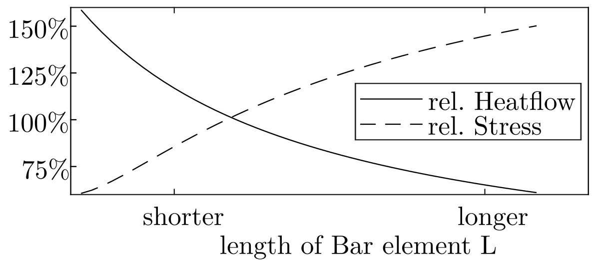

Fig. 3. Heat flow and stress over bar element length [1]

3. Problem Analysis

Thermal stress is not the only stress that structures have to endure. It is also produced by the structure as a result of an inefficient design [1]. If heat flow is designed according to the structure and thermal loads, thermal stress can be reduced [1, 7]. An efficient component utilizes every single one of its elements to (or close to) its limit [9, 10, 11]. The question comes up of which stresses are necessary for the function. External forces must be endured; everything else is structure born and, therefore, can and should be minimized. To be able to do that, each element's cause of stress must be understood. In this paper, stress is named and separated by its cause, so when optimizing a structure for stress, the right tool can be used to manage it. Here three types of stress are taken into account: Mechanical Stress (M-Stress) is caused by external forces that must be transferred from the source to the sink. Optimizing for mechanical stresses means reducing the density of regions subjected to low stress or compliance to increase the stiffness-to-mass ratio, therefore removing regions that are not needed for the transfer. Elevated temperatures reduce allowable stress. The designer must choose whether this is the elastic, plastic, or fatigue limit.
Thermal Stress (T-Stress) is a concept introduced here to evaluate the impact of this limit reduction. Figure 1

displays the concept. Instead of reducing the limit over temperature, the limit stays constant, and a phantom stress (T-Stress) is introduced. It mirrors the loss in stress limit and therefore makes the impact of temperature-dependent on stress limit reduction comparable to other load types. Thermo-mechanical stress (TM-Stress) is mechanical stress resulting from forces caused by a part attempting to expand or contract when it is constrained [1]. Constraints can be regions with different temperatures and, therefore, different expansion. Figure 2 displays a simplified model of this behavior in a steady state. The bar element at the center has a length L and a cross-sectional area A, a heat conductivity of λ, and a thermal expansion coefficient α. On the left and right sides are springs with a stiffness of k representing the elements next to it. From the left, a heat source with the temperature T_0 and a heat transfer coefficient (HTC) of $h_{0,1}$ is set, and on the right is the thermal sink located, with the HTC $h_{2,3}$ and the sink temperature T_3. The element has a linear temperature gradient between T_1 and T_2. To calculate the thermal behavior the thermal resistances $R_{n,m}$ between the Temperature levels T_n and T_m have to be examined:

$$\begin{aligned} R_{0,1} &= (A \cdot h_{0,1})^{-1} \\ R_{1,2} &= L/(A \cdot \lambda_{1,2}) \\ R_{2,3} &= (A \cdot h_{2,3})^{-1} \end{aligned} \tag{1}$$

This enables the calculation of the heat Q that transfers through the element

$$\begin{aligned} Q &= (R_{0,1} + R_{1,2} + R_{2,3}) \cdot (T_0 - T_3) \\ Q &= R_{0,1} \cdot (T_1 - T_2) \end{aligned} \tag{2}$$

The mean expansion of the bar ϵ depends on thermal expansion and forces, like the springs displayed in figure 2

$$\epsilon = L \cdot \alpha \cdot \frac{T_1 - T_2}{2} + \frac{F \cdot L}{A \cdot E} \tag{3}$$

to calculate the TM-stress:

$$\sigma_{TM} = \frac{\alpha \cdot E \cdot (T_1 - T_2)}{1 + (A \cdot E)/(k \cdot L)} \tag{4}$$

Figure 3 displays heat flow and TM-stress over bar length. Reducing the length reduces the thermal resistance. Therefore more heat can flow with a lower temperature difference. The reduced temperature difference results in smaller expansion and lower stresses. Consequently, removing elements between the thermal source and sink can reduce stresses. Utilizing this principle helps optimize components for an efficient design. The next chapter will present a development environment that utilizes the effect. An application example is provided afterward.

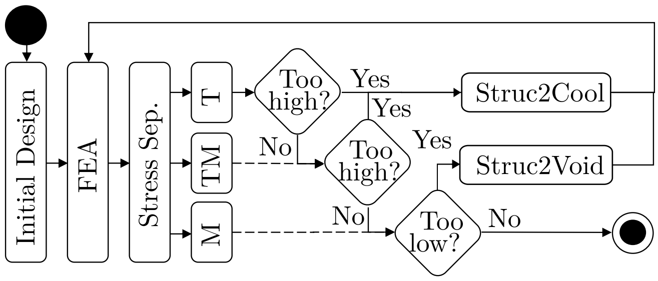

Fig. 4. Optimization for thermal mechanical Stress

4. Optimization

Adding up T, TM, and M stresses gives an impression of how close an element is to its limit. Separating them allows for precise management of stresses. The separation creates the following most likely cases:

- Exceedingly high T-Stress: More Cooling is needed; reduce distance between source and sink [1].
- Exceedingly high TM-Stress: The distance between source and sink has to be reduced close to the element with the high TM Stress [1]
- Low M-Stress: Remove elements/reduce density [9, 12]
- High M-Stress is desirable if it does not exceed the limit. It is an indication of optimal utilization of the material.
- Low TM-Stress is also desirable because it implies that the element is not stressed by neighboring elements and has more room for M or T-stress.
- High T-Stress implies hot surfaces; if below the limit, it can be favorable because it reduces energy losses from the exhaust to the component.

Figure 4 displays the process. It starts with an initial design which is discretized for use in a Finite Element Analysis (FEA) Tool. The initial design needs a preexisting cooling channel with minimal size. The channel can be chosen concerning components close by that feed the channel. The initial cooling channel will not be removed but only extended. Additionally, the initial design must be capable of withstanding the mechanical loads. In the next step, a FEA is performed with all the thermal and mechanical boundary conditions in place. The result can be exceedingly high stress in certain elements. The stress is separated into M-, T-, and TM-stress as described in chapter 4. All elements will be analyzed, starting with those above the stress limit. All stress types are being analyzed for the analyzed element, whether they are too high or too low. Describing and formulating these limits has to be chosen by the designer. Which stress should be countered when an element is loaded with all three stress types and the sum exceeds the limit? Temperature is favorable if it does not exceed the materials limit set. If temperatures are higher, more cooling is needed. In the next step, it is tested whether the TM-stress is too high. Again the question has to be asked how high is too high? The M-stress is con-

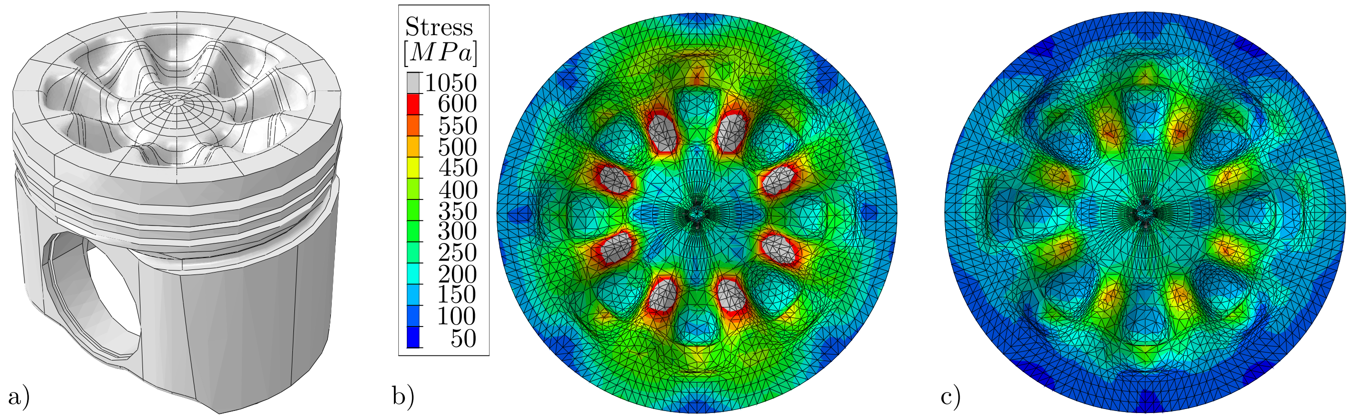

Fig. 5. a) Piston with advanced bowl shape; b) Stress on piston bowl initial design; c) after optimization

sidered necessary to transfer the forces, while TM-stress is a sign of inefficient thermal management. Therefore if overall stress exceeds the limit and TM-Stress is involved, it must be counteracted. This is done in the same way as reducing the T-stress. In this function (abbr. in figure 4 as "struc2cool"), an element made out of structural material (e.g., steel) which is adjacent to the cooling channel and closest to the chosen element is picked. This second element is turned into void, and its faces are given the same surface properties as they would have been part of the cooling channel. Additionally, it labels the new cooling channel adjacent elements and converts neighboring void elements into cooling channel elements. The process is repeated as long as no elements exceed the limit. After that, only a certain amount of elements are modified. After that, the elements are analyzed with the lowest amount of stress. Finally, elements that do not bear any load can be turned to void (abbr. in figure 4 as "struc2void"). Several papers have been written on this process with many types of optimizers like SIMP [9], BESO [12] and IZEO [13].

5. Application

In compression ignition engines, the interaction of the fuel jets and the piston bowl significantly influences the combustion and pollutant formation process. Large-diameter combustion chambers combined with shallow dish bowl shapes allow a longer free spray path length reducing the wall impingement at high injection pressures. Thus, such bowl shapes are the overall design for heavy-duty applications[14]. To combine these benefits with the capability of guiding the fuel jets to zones of the lean mixture and prohibiting the merging of adjacent jets forming rich mixtures at the piston bowl surface, a 3D CFD investigation was undertaken to design an innovative bowl shape for heavy-duty applications. Figure 5a) shows the newly designed bowl shape, featuring a long free spray path length and individual spray pockets shaped to guide the jets into the center of the combustion chamber segmented by ridges. This overall design leads to a highly inhomogeneous thermal load on the bowl surface. On the one hand, the spray flame interacts locally with the individual pockets' bowl surface, creating locally high heat transfer coefficients of up to 2100 $\frac{W}{Km^2}$ at surface temperatures of 2000 K. On the other hand, the segmenting ridges are exposed to a significantly lower heat flux of 600 $\frac{W}{Km^2}$ at 1000 K. The piston is cooled with an internal cooling channel constantly flushed with oil at 400 K and a HTC of 1500 $\frac{W}{Km^2}$ [15]. The distance between the bowl and the cooling channel is 7 mm minimum and 35 mm to the

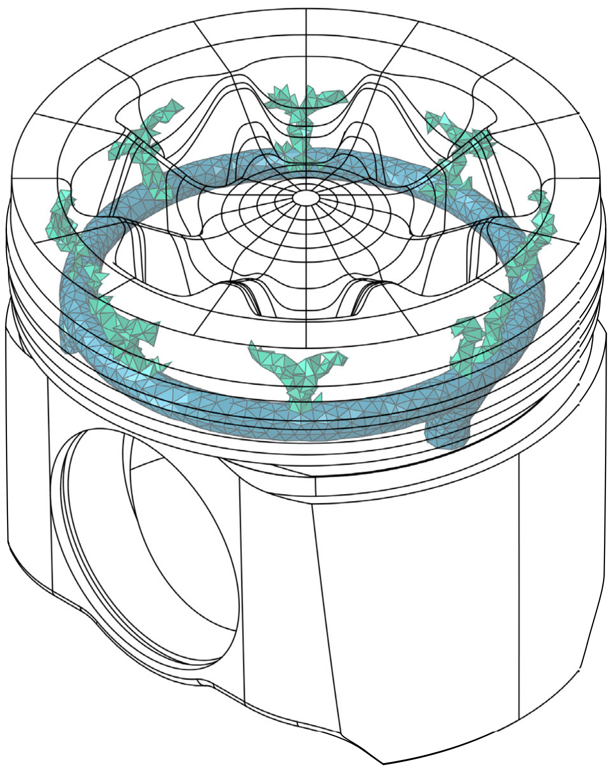

Fig. 6. Cooling Channel grown by Optimization
blue: Initial Design; stress level figure 5b),
blue+green: optimized design; stress level 5c)

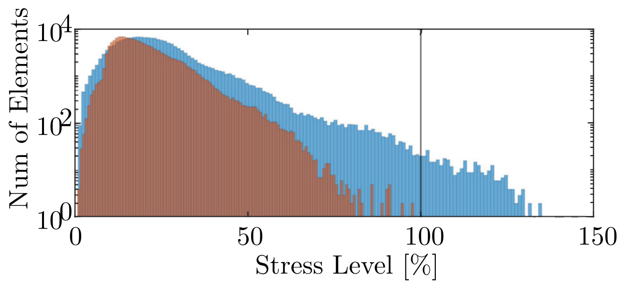

Fig. 7. Distribution of rel. Stress as a percentage of the limit in initial design (blue) and after TM optimization (red)

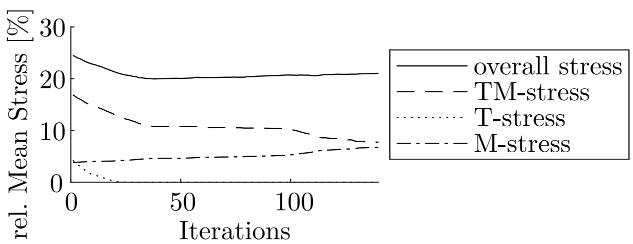

Fig. 8. Mean stress separated by type over iteration

top. Additionally to the heat, high mechanical forces from the combustion must withstand. Here a peak pressure of 23.5 MPa has been applied to the bowl. To reduce simulation time, forces are transferred to an elastic foundation at the pin bore and skirt instead of a modelling the contact with a pin or liner. With this type of thermal input, high TM-Stress occurs when the cooling channel is not designed correctly. The complicated shape of the bowl in addition to the uneven heat flow demands an elaborate shape of the channel. Additionally, the cooling channel has to be close to the bowl surface to reduce T-stress. On the other hand, the M-stress demands a thick-walled design to withstand the pressures from the combustion. The process of creating the preliminary design of the piston is displayed in figure 4. For the presented piston, the stress level on the surface of the bowl is shown in figure 5b) and 5c). Figure 5b) shows the initial design with stresses exceeding the limit by 180 MPa or 130 % and in figure 5c) after the growth of a cooling channel, the stresses are much lower due to a more efficient cooling channel design. The cooling channel designed in this process is shown in figure 6. The piston is displayed transparently. Inside the piston, the initial cooling channel is displayed in blue, and the grown channel is green. The piston with only the blue channel is the initial design (see figure 4) and results in the stress field displayed in figure 5b). The optimized design keeps the initial cooling channel (blue) and adds the green structures. The new topology has the stress distribution shown in figure 5c); therefore, displaying that the removal of material can remove stress. This is supported by the stress distribution shown in figure 7. Here a histogram collects the distribution of stress levels per element. The stress level is the non-separated overall stress, with 100 % being the failure limit. The initial design is shown in blue, and the TM-optimized version is in red. The distribution is typical for an initial thermal design. Most elements utilized less than 30 %, but some elements will break over the 100 % limit. After the removal of the correct elements, therefore, by reducing structural material, the exceedingly high stresses were removed. The structure is now able to withstand the load. Nevertheless, it could be improved. Still, many elements bear a small load, and a mechanical optimization as described in, e.g., BESO [12, 13] must be performed. For thermo-mechanical stress, this is also beneficial because thermal expansion is accommodated, and thermal stress is relieved. Figure 8 displaces the mean stress of the piston over each iteration. Each iteration element was turned into a cooling channel or void. In this design, only structural elements are evaluated. The solid line shows the overall mean stress over each iteration. While it plunges in the first iterations, it afterward steadily increases. To understand the behavior, the different types of stress are also displayed. The dashed line shows the TM-stress, which decreases with each iteration. This fits the behavior shown in figure 7, where the peak stress levels are dispersed. The dash-dotted line shows the M-Stress, and as expected, the average stress increases with iterations due to the removal of low-stressed elements. This also causes the remaining elements to take higher loads. T-Stress is low in the initial design and declines further with more cooling.

With the proposed approach, the piston under thermo-mechanical load has been optimized. As a result, exceedingly high stress was reduced below the material's limit, while mechanical stress got distributed more efficiently.

6. Summary and Outlook

Due to the inherent complexity of thermal structures, designing these components is considered challenging. Therefore, a heat sink needed to be included in the initial design to start a topology optimization as described by Meng et al. or Gao et al. [4, 6]. Therefore, a new method is applied to skip this complex task for the initial design. By separating stress by its cause, different actions are needed. The discussed stress types and their causes are:

- M-Stress caused by forces
- TM-Stress from thermal expansion of an element which is constraint by neighboring elements or boundary conditions
- T-Stress phantom stress that is introduced to emulate the reduction of stress limit over temperature

M-Stress is necessary to carry a load, but TM-stress, as structure-born stress, can be reduced if too high. By reducing the thermal resistance between the source and sink, the stress decreases as well. It has been shown that only a tiny initial sink is needed to optimize a structure with a complicated 3D shape. The result is a viable structure with a fitted cooling channel and the potential to optimize further the structure regarding mechanical topology. By including the temperature-dependent heat flow, the model is much more realistic than other approaches for optimization. On the other hand, several simplifications have been made. The HTC in the cooling channel changes over the piston's reciprocation and, more importantly, for steady-state analyses, with the surface angle and height [15]. Therefore new HTCs have to be calculated for every surface. This could be done in CFD or with a rule-based system. However, the calculation and verification are computation-intensive, time-consuming, and expensive. Therefore values from the literature and sensitivity analysis are recommended for the early stages of development. The calculation for thermal stress is done as a steady state. Also, thin cooling channels can inhibit the oil flow, so rules for optimal shapes should be implemented in future designs similar to manufacturing restrictions proposed by Siqueira et al. [13]. The shown optimization is stress focused with a penalty for high temperatures (see T-Stress, figure 1). For applications that make use of combustion processes, high or specific surface temperatures are favorable. Therefore the inclusion of a temperature restriction into the method can be valuable. The reduction of Young's Modulus over temperature is integrated into the FE calculation but not considered in the optimization. Increasing the temperature level while maintaining the ΔT would therefore reduce TM-stress. One method for that would be the introduction of isolation channels in the design proposed by Krause et al. [16]. For topology optimization, this would imply the introduction of air or other isolating fluids into the optimization. The fluids would also enable thermal expansion without constraints and help reduce thermal stress. Another method for higher surface temperatures would be to control the coolant in the channels and reduce the HTC or temperature when favorable. The thermal simulation has been done for a steady state; heat up to a steady state is transient, and this is where high thermal loads can occur [1]. While the optimization favours thin-walled structures, which are less vulnerable to transient thermal stress, the method has to be tested in the future. Manufacturing Restrictions, as described in [13] for conventional manufacturing or [17] for additive manufacturing, could be added to create a more net-shaped design.

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