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Topology Optimization for Efficient Support Structure Designs in Additive Manufacturing



Rajit Ranjan, Prabhat Kumar, Can Ayas, and Matthijs Langelaar

Abstract In Metal Additive Manufacturing (MAM), support structures serve not only for mechanical supports but also for heat dissipation, preventing overheating in the melt zone. Although a high support volume aids heat dissipation, it significantly increases printing time, material wastage, and post-processing efforts. Additionally, contact area between the part and the supports often has higher surface roughness, which compromises part quality. This paper presents a novel density-based Topology Optimization (TO) technique for designing support structures optimized for efficient heat evacuation while keeping the part design fixed. First, a simplified MAM model, already established in the literature, is used to identify regions prone to overheating, referred to as 'hotspots.' This hotspot information is then used to formulate a TO problem that minimizes support volume while regulating the heat evacuation efficiency of the supports through thermal compliance which is defined as a constraint. For calculation of thermal compliance, a thermal load is defined using the hotspot information while the baseplate acts as a heat sink. To reduce post-processing costs, a concept of vicinity penalization is introduced, promoting the minimization of the part-support interface area. First, a set of 2D results is presented to demonstrate the method's effectiveness and explain the influence of various parameters. Next, the TO algorithm is applied to a real-size 3D part and the results are discussed. Finally, the performance of the optimized supports is evaluated using a transient layer-by-layer AM simulation.

Keywords Topology optimization · Additive manufacturing · Support structures

R. Ranjan (✉)
Department of Mechanical Engineering, Indian Institute of Technology, Jodhpur, India
e-mail: rajitranjan@iitj.ac.in

P. Kumar
Department of Mechanical and Aerospace Engineering, Indian Institute of Technology Hyderabad, Kandi, Telangana, India

C. Ayas · M. Langelaar
Department of Precision and Microsystems Engineering, Delft University of Technology, Delft, The Netherlands

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1 Introduction

Additive Manufacturing (AM) technologies offer unprecedented design flexibility, because of which the popularity and usage of AM techniques are increasing for fabricating highly efficient and complex industrial parts. Powder bed fusion (PBF) processes are the leading AM techniques for fabricating metal parts, and high-energy beams are used to fuse metal powder in a layer-by-layer manner. Laser-based powder bed fusion (L-PBF) and Electron beam-based powder bed fusion (EB-PBF) are examples of such processes. In both these techniques, the manufactured specimens generally consist of the functional part and the sacrificial support structures. The latter are employed to facilitate defect-free manufacturing of the former.

There are three primary purposes associated with the functioning of the supports. First and foremost, they are used as heat evacuating members and to prevent local overheating near the melt zone. LPBF parts remain immersed in the powder bed with all lateral surfaces in contact with the unmolten powder, which has approximately 1% of the thermal conductivity of the bulk material [11, 15]. Due to this, the geometrical features that restrict adequate heat evacuation, e.g., acute overhangs, cause local overheating [9], which is highly detrimental to the part quality. Craeghs et al. [3] conducted in-situ monitoring of the melt pool and demonstrated that inadequate heat dissipation leads to an enlarged melt pool. The same study demonstrates that reduced overheating can be achieved by using support structures with relatively more uniform temperatures. On the other hand, if heat distribution is uneven and cyclic, it can contribute to the formation of residual stresses and, subsequently, part distortions. Note that the supports add stiffness, resulting in less distortion. Additionally, features with long overhangs cannot sustain their self-weight, thus posing difficulties when printing using layer-by-layer AM approaches. Therefore, supports act as load-bearing members to carry the structural load of the part. This paper focuses on the heat evacuation aspects of the supports and proposes a novel method for designing efficient support structures. A brief literature review of the existing support design methodologies is presented next.

One can categorize different support design methodologies primarily into two groups: manual design and topology optimization-based approaches. The former uses predefined structures in a repeated fashion to reduce the support volume. Typical examples of such shapes are tree-like structures [18], lattice shapes [16], bridge-like scaffolds [4], and sloping wall structures. The manual methods are highly dependent upon the designers' expertise and may fail to provide the necessary support for a specific part. However, topology optimization (TO) is a systematic numerical approach that finds optimized structures for achieving the desired functionality under given constraints. Therefore, the approach presented in this paper utilizes TO formulation aiming to address manufacturability during the design process.

One can classify the support design TO approaches into two groups. The first group comprises techniques that deliver designs already optimized from the context of support requirements. For example, the AM filter presented by Langelaar [6] performs a printability check and finds optimal part designs without support. Similarly,

multiple formulations have been proposed that focus on optimizing part design so that support requirements are minimal [7]. However, the pursuit of fully self-supporting designs imposes limitations on the design space. As a result, the overall performance of the part is often compromised. To tackle this issue, researchers have developed TO approaches that specifically target support optimization while keeping the part design unchanged.

In this regard, significant research attention has been given to developing novel TO methods which aim to develop thermally efficient supports. For example, Zhou et al. [19] coupled a simplified transient AM model in density-based TO for finding support designs which reduce temperatures at certain pre-specified points. Allaire et al. [1] coupled thermal and thermo-mechanical AM models with level-set TO for the purpose of designing efficient supports. More recently, Miki and Nishiwaki [10] and Haveroth et al. [5] also coupled transient AM thermal models within TO for the purpose of support optimization. While promising, these approaches are anticipated to be computationally intensive, as transient AM simulations are already very computationally expensive. Integrating them with TO further exacerbates the computational load, often resulting in impractically long run times for real-scale parts. In this paper, we propose to utilize an extremely fast AM model, already established in literature, as a pre-optimization step. Using this model, overheating information about a given design can be quickly obtained. This information is further utilized to formulate a computationally fast TO problem for support structure designing.

The remainder of the article is organized as follows. The TO formulation is discussed in Sect. 2 while 2D and 3D results are presented in Sect. 3. A high-fidelity AM thermal model is used to evaluate the performance of the optimized supports and the results are presented in Sect. 4. Finally, conclusions are outlined in Sect. 5.

2 Topology Optimization

The proposed support optimization algorithm begins with an LPBF part represented by Ω. In this approach, (i) the part Ω and its build orientation are fixed, (ii) the support structures are optimized to minimize volume and part-support contact area that ensures sufficient heat dissipation. As per [12], minimizing the contact area is required, as it directly affects the post-processing. The robustness and success of the presented method are demonstrated on an inverted L-shaped design (Fig. 1a); however, it can be used for another set of designs. We provide the entire process below first, while other details followed in subsections.

1. The process begins with an analysis of the fixed part Ω using a layer-by-layer thermal AM model per [11]. This model has proven effective in identifying overheating regions within a part. The resulting overheating data, referred to the hotspot field, is denoted by $\mathbf{T}_{\mathrm{HS}}(\Omega)$. More details on this thermal modeling is mentioned in Sect. 2.1.

2. Next, we calculate the virtual heat load $\mathbf{Q}_{\text{vir}}$ having the same spatial distribution as $\mathbf{T}_{\text{HS}}$. Considering virtual heat flux as a heat load with baseplate (bottom) of the domain as heat sink, a new boundary value problem is defined. This definition is based on the observation that the highest temperatures occur in regions prone to overheating. Since $\mathbf{Q}_{\text{vir}}$ is proportional to temperature, it effectively represents the heat dissipation requirements. This virtual load does not correspond to the actual heat flux from the moving laser; rather, it serves as an indicator of potential overheating in the absence of support structures. Remark here that, this is one of the ways to define the load in TO, one can explore other alternative to this.
3. The optimization problem aims to minimize the support volume. Additionally, a novel vicinity penalization scheme is incorporated, introducing penalty weights in the objective function to reduce the part-support contact area.
4. The thermal compliance quantifies the heat evacation performance of the support structures, whereas it is controlled using the constraint in the optimization problem. To establish a reference value, a best-case scenario is considered, where the entire design domain is filled with support material. The corresponding thermal compliance is computed in a pre-optimization step, enabling the formulation of the thermal compliance constraint.
5. Finally, the TO problem, which aims to minimize support volume and part-support contact area while enforcing thermal compliance as a constraint, is solved using the Method of Moving Asymptotes (MMA) [17].

2.1 Calculation of Virtual Heat Load

As mentioned before, at the initial step, we apply the simplified AM thermal model to the part design Ω for identifying the critical overheating zone and for generating $\mathbf{T}_{\text{HS}}(\Omega)$. We adopt the model presented in Ranjan et al. [13], wherein simplifications were performed to detect overhearing in the AM parts effectively. Later, this model was integrated with the density-based TO and experimentally validated to overheat in [11, 14]. Figure 1b depicts the hotpost map $\mathbf{T}_{\text{HS}}(\Omega)$ obtained using the simplified AM model for the inverted L shape. The employed discretization scheme is similar to that mentioned in Ranjan et al. [11], wherein the element densities are represented by $\tilde{\boldsymbol{\rho}}$ vector. Next, one calculates the virtual heat flux using the hotspot map as

$$\mathbf{Q}_{\text{vir}} = f_{\text{s}} \frac{\mathbf{T}_{\text{HS}}}{\max(\mathbf{T}_{\text{HS}})}, \tag{1}$$

where f_{s} is a scaling factor. The heat flux is determined here in terms of the magnitudes of the nodal heat fluxes. To control the magnitude of $\mathbf{Q}_{\text{vir}}$, a normalization factor $\max(\mathbf{T}_{\text{HS}})$ is used. As stated in Sect. 2, this heat load definition is motivated by the fact that regions with high hotspot temperatures signify overheating and necessitate efficient heat dissipation.

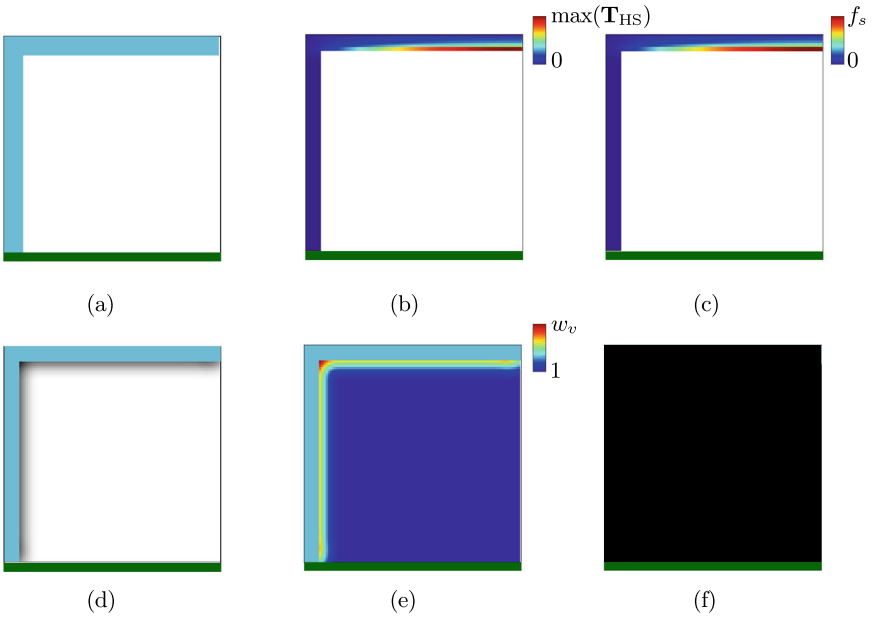


Fig. 1 **a** Inverted L shape part Ω used to illustrate the support optimization algorithm. **b** $\mathbf{T}_{\mathrm{HS}}(\Omega)$ obtained using the simplified AM model. **c** $\mathbf{Q}_{\mathrm{vir}}$ evaluated using $\mathbf{T}_{\mathrm{HS}}(\Omega)$, scaling factor f_{s}, so that $\max(\mathbf{Q}_{\mathrm{vir}}) = f_{\mathrm{s}}$. **d** Filtered density field with $R = 6$. **e** The vicinity penalization field is used to minimize the part-support contact area. **f** Ω with fully solid support provides reference thermal compliance

2.2 *Defining the Vicinity Penalization Field*

The key criterion to design efficient supports is to minimize the part-support area [12]. The post-processing cost increases with an increase in the support contact area as its removal is needed. In addition, further finishing steps are needed to circumvent the high surface roughness at the part-support interface. In this work, we introduce a penalization zone near the surface part that guides the optimizer in finding the trade-off between the effective heat dissipation through the support structure and the abundance of material close to the part.

We use the density filtering scheme Bruns and Tortorelli [2] for defining the vicinity penalization zone for the given part. It is well known that this filtering was initially proposed to subdue the checkerboard patterns in the TO while imposing a length scale. The scheme is employed for its original intended purpose, which is mentioned in Sect. 2.4. This scheme functions by defining the filtered density of each finite element as the weighted average of the densities of neighboring elements within a distance R from its center, where R is known as the filter radius. We also identified that the same filtering scheme can be effectively used for penalizing the zone near the part, which is explained below.

We apply the density filtering on the parameterized domain part Ω which results in a domain with filtered density field, denoted as $\tilde{\Omega}$ (see Fig. 1d). One notices that the density field decays as we move away from the part boundary, in which the delay distance is controlled by filter radius R. The entire field is multiplied by a weight factor w_{v} and then unity is added to get the final vicinity penalization contours as depicted in Fig. 1e. As desired, the field gives a high penalization value near the part while it decreases as one moves away from the part with the value of 1 far away from the part. Since this field is intended to regulate material distribution exclusively within the support design domain, it is applied only to the support region and ignored for elements that belong to the part. We define a vector $\mathbf{L}$ that contains the vicinity penalization field and has the same order as of $\tilde{\boldsymbol{\rho}}$. The objective function is formulated using $\mathbf{L}$ and $\tilde{\boldsymbol{\rho}}$ as $J = \mathbf{L}^T \tilde{\boldsymbol{\rho}}$. In fact, J returns a weighted sum of elements' volumes, with weights coming from the constructed vicinity penalization field, which is minimized, eventually leading to the minimization of the support volume. Remark that vector $\mathbf{L}$ is independent of the design variable, thus, defined once before the optimization. Additionally, the support-part contact area is minimized, as a higher cost is assigned to adding material near the part. The weight factor w_{v} serves as a parameter to control the strength of this penalization effect, and its influence is further analyzed later in Sect. 3.

2.3 Calculation of Reference Compliance

In this work, the primary aim of the optimization process is to minimize the support volume under a thermal compliance constraint that helps evaluate and regulate the heat evacuation efficiency of the support. To evaluate the lower bound on the thermal compliance or the reference value c_{ref}, a fully filled solid support is considered as depicted in Fig. 1f. Next, we construct a constraint using the thermal reference compliance c_{ref} and structure compliance as

$$\eta \frac{c}{c_{\mathrm{ref}}} - 1 \leq 0. \tag{2}$$

η determines the heat evacuation efficiency of the supports. $\eta = 1$ indicates fully solid supports. Note that, the selection of η directly affects the volume of the support material required to achieve the target efficiency. More details regarding the same is mentioned in Sect. 3.

2.4 Support Optimization Formulation

The optimization problem for the support can be now written as

$$\min_{\boldsymbol{\rho}} : \; J(\boldsymbol{\rho}) = \mathbf{L}^T \tilde{\boldsymbol{\rho}}, \tag{3a}$$

$$\text{subjected to:} \tag{3b}$$

$$c = \mathbf{Q}_{\text{vir}}^{T}\mathbf{T}(\tilde{\boldsymbol{\rho}}), \tag{3c}$$

$$\eta\frac{c}{c_{\text{ref}}} - 1 \leq 0, \tag{3d}$$

$$\mathbf{GT} = \mathbf{Q}_{\text{vir}} \tag{3e}$$

$$\mathbf{0} \leq \boldsymbol{\rho} \leq \mathbf{1}. \tag{3f}$$

Here, $\boldsymbol{\rho}$ indicates the design variable vector. Equation (3e) represents the discretized version of the heat equation, where $\mathbf{G}$ denotes the global conductivity matrix and $\mathbf{T}$ represents the nodal temperatures. Equation (3c) gives the definition of the thermal compliance. In addition to defining the vicinity penalization zone, the density filtering scheme Bruns and Tortorelli [2] is employed to achieve minimum length scale and prevent checkerboard patterns. The filtered density is evaluated as:

$$\tilde{\rho}_e = \frac{\sum w_{e,i}\rho_i}{\sum w_{e,i}}, \tag{4}$$

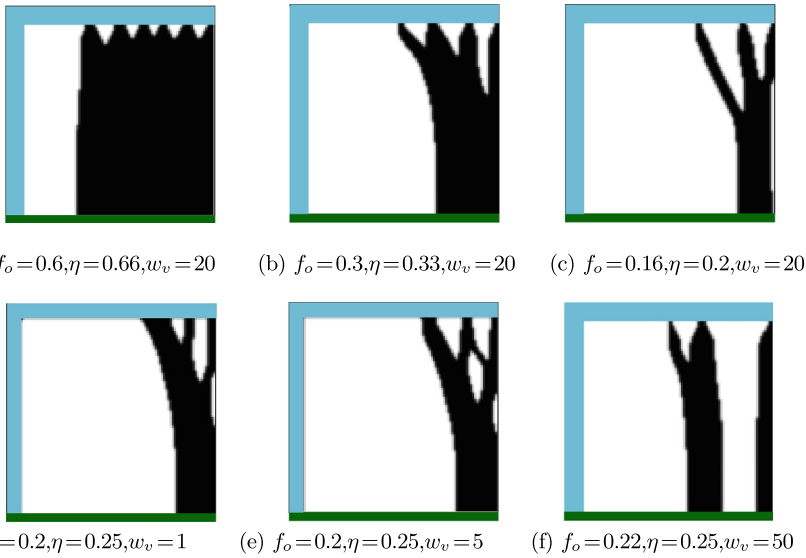
where, $w_{e,i} = \max(0, R - ||\mathbf{r}_i - \mathbf{r}_e||)$. $\mathbf{r}_e$ and $\mathbf{r}_i$ indicate the center of element e and element i, respectively. $R = 1.5$ and $R = 2.5$ is used for 2D and 3D, respectively.

3 Results and Discussion

This section presents 2D results using the inverted L shape introduced earlier to frame the problem. In addition, we examine the effects η and w_v for the 2D problems. The method is extended thereafter to the 3D cases to demonstrate its versatility.

3.1 2D Results

We present a series of results for the inverted L shape case in Fig. 2. Typically, the support optimization renders tree-like structures that connect the most highly heated overhanging regions to the baseplate, facilitating heat evacuation. The impact of η is illustrated in Fig. 2a–c. One notices that thinner structures are generated as η decreases. The same is reflected in the reduction of total support volume with lower values of η. In addition, one notes the effect of the vicinity penalization weight w_v in Fig. 2d–f. The figures show a clear tendency to reduce the part-support interface area as w_v increases.



(a) $f_o = 0.6, \eta = 0.66, w_v = 20$ (b) $f_o = 0.3, \eta = 0.33, w_v = 20$ (c) $f_o = 0.16, \eta = 0.2, w_v = 20$

(d) $f_o = 0.2, \eta = 0.25, w_v = 1$ (e) $f_o = 0.2, \eta = 0.25, w_v = 5$ (f) $f_o = 0.22, \eta = 0.25, w_v = 50$

Fig. 2 Inverted L shape part with optimized supports. **a**–**c** Present the results with different efficiency η and a constant vicinity penalization weight $w_v = 20$. Each result also indicates the volume fraction for supports f_o. One can see that relatively more support material is needed for the deemed thermal compliance constraint with a higher η. **d**–**f** Depict the results for varying vicinity penalization weight with a constant $\eta = 4$. One notes that the part-support contact area diminishes with an increase in w_v

3.2 3D Results

The part shown in Fig. 3a is selected for demonstrating the novel support optimization algorithm. In an earlier study [14], this design was experimentally analyzed for overheating and hence, the availability of overheating information is the motivation behind our choice. In the previous work, the design was fabricated in an EOS M290 machine and monitored by an EOSTATE exposure optical tomography (OT) system. The OT values correspond to the integrated radiation from the melt pool region over the period of time for each layer deposition. Hence, they indicate overheating behavior during the AM process. The OT values for the considered part are shown in Fig. 3b. It was observed that the top funnel shaped features, highlighted by red arrows in Fig. 3a, show a clear tendency of overheating as evident by increased density of high OT data points in this region. For further details about the experiment, readers are referred to Ranjan et al. [14].

The TO problem given in Eq. 3 is solved by discretizing the design domain into a grid of $120 \times 40 \times 40$ hexahedral elements in x, y and z directions, respectively. Results after 200 iterations are shown in Fig. 3c–f. In order to present the detailed view of the supports, the part has been made transparent in Fig. 3e. The results are shown for $\eta = 15$ and $w_v = 400$ while other TO parameters are same as reported in

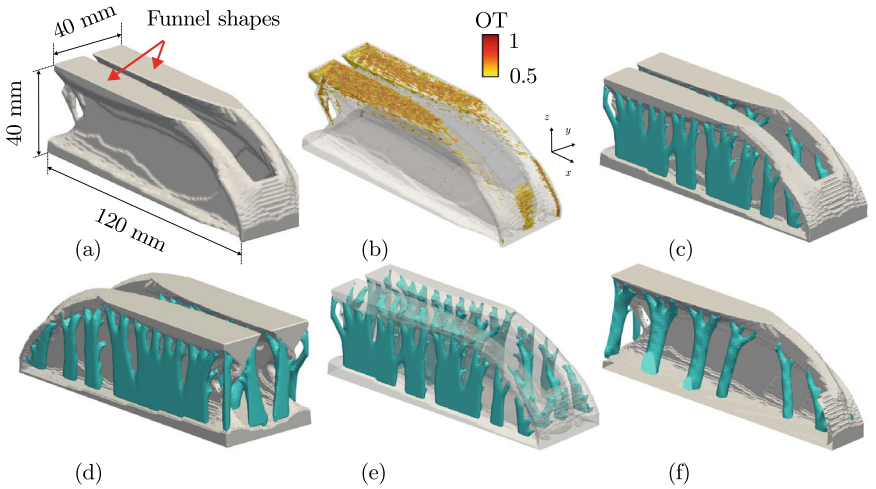


Fig. 3 **a** Design considered for implementing the novel support optimization scheme. **b** Experimental OT data showing the overheating tendencies associated with funnel shapes (highlighted with arrows) [14]. **c**, **d** The optimized supports (in cyan color) found using the proposed support optimization algorithm. **e** Full view of supports with part design made transparent. **f** Sectional view is shown to highlight internal features

Liu and Tovar [8]. The algorithm tends to generate tree-like supports with branches thinning near the part-support contact for easy removal. More critically, thicker supports are generated for effective heat evacuation in the funnel regions of the part, which were identified as a cause for overheating (see Fig. 3b). This demonstrates the efficacy of the optimized supports for heat evacuation from the critical regions prone to overheating. Finally, Fig. 3f presents a sectional view of the part and supports, revealing the internal features of the generated supports.

4 Verification Using Higher Fidelity Thermal Model

In order to evaluate the performance of optimized supports, the part and supports are subjected to a high-fidelity transient AM simulation based on a layer-by-layer deposition scheme. As opposed to the simplified AM model which was used to find the hotspot fields, the high-fidelity simulation considers transient heat deposition, thermal losses due to convection and radiation, and, temperature dependent thermal properties. Note that, due to simplifying assumptions of layer-by-layer energy deposition, the temperatures predicted by the high-fidelity simulations do not represent actual process temperatures. Instead, they signify overheating tendencies associated with different geometrical features within the part. For details about the high-fidelity model, readers are referred to Ranjan et al. [13].

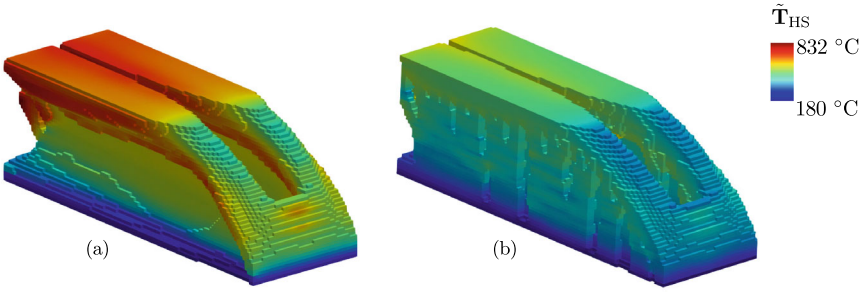


Fig. 4 **a** The hotspot map $\tilde{\mathbf{T}}_{\mathrm{HS}}$ obtained from the high-fidelity transient layer-by-layer AM simulation for **a** part without support and **b** with optimized supports. A 35% reduction of maximum temperature is achieved, indicating the utility of the proposed approach

Figure 4a, b present the hotspot fields $\tilde{\mathbf{T}}_{\mathrm{HS}}$ obtained using the higher fidelity model for the design shown in Fig. 3a, c, respectively. Owing to the presence of optimized supports, there is a 35% reduction in the peak temperatures. Since the supports will be removed from the component, they do not have strict print quality requirements and hence can have steep overhang angles leading to a maximum temperature of 590 °C. However, the maximum temperature within the part is reduced to 540 °C from 832 °C when the process simulation is performed in the absence of a support structure.

5 Closure

This paper presents a novel TO scheme that is able to generate thermally efficient support structures for a given AM part. A computationally inexpensive AM thermal model is taken from the literature and coupled with density-based TO. A constraint is formulated to achieve the desired value of thermal compliance, which is used as a measure of the heat evacuation capacity of supports. Additionally, a vicinity penalization scheme is introduced to prohibit part-support contact. 2D results are presented, and a short discussion on optimization parameters is provided. A result for a real-size 3D part is also presented showcasing the scalability of the proposed approach. Finally, a high-fidelity transient layer-by-layer thermal model is used to verify the efficacy of proposed supports on heat evacuation.

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