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7th TOP Webinar

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Topology optimization of support structure layout in metal-based additive manufacturing accounting for thermal deformations

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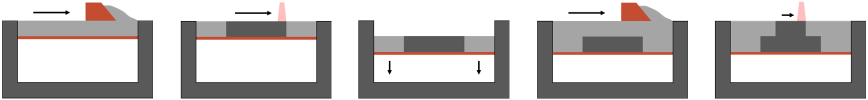
Metal-based additive manufacturing

Selective Laser Melting (SLM):

- A re-coater deposits a thin layer of metal powder on the build platform.
- A high-energy laser traces the first section of the part.
- The build platform is lowered.
- The re-coater deposits a thin layer of powder on the previous layer.
- The laser traces the next section.

This process is repeated until the entire part is built.



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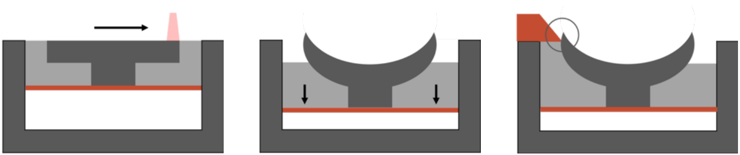
Problem statement

Thermal deformation of the part during manufacturing can cause failure:

- Heating and cooling cycles induce internal stresses in the part.
- Internal stresses cause deformations during manufacturing.
- Upward displacements larger than the thickness of a layer cause re-coater collisions, resulting in print failure.



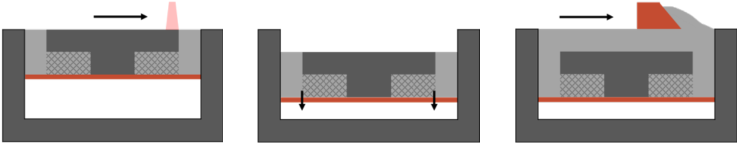
Problem statement

Sacrificial support structure is added in order to:

- support horizontal layers during manufacturing.
- improve heat transfer to build platform.
- reduce vertical displacement of individual layers.

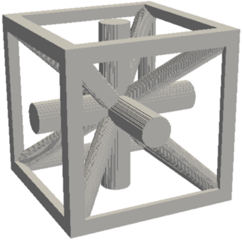
In current practice, support structures are designed manually.

Our aim is to design it by means of numerical optimization, to reduce sacrificial support material consumption as well as printing time.



Simulation of thermal deformations

The support structure is modeled as a homogenized lattice structure with the isotruss layout.



$$\frac{E^{\mathrm{h}}}{E_{\mathrm{S}}} = (0.20529 - 0.03303\nu_{\mathrm{S}})\rho + (0.08121 + 0.27243\nu_{\mathrm{S}})\rho^2 + (0.64974 - 0.24237\nu_{\mathrm{S}})\rho^3$$

$$\nu^{\mathrm{h}} = (0.24776 + 0.01698\nu_{\mathrm{S}}) - (0.15929 - 0.73860\nu_{\mathrm{S}})\rho - (0.18628 + 0.48323\nu_{\mathrm{S}})\rho^2 + (0.09775 + 0.72660\nu_{\mathrm{S}})\rho^3$$

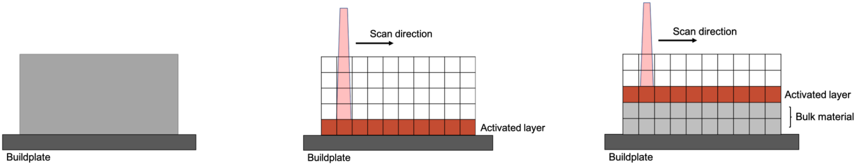
$$d = 0.02049 + 1.05076\rho - 1.59468\rho^2 + 1.09799\rho^3$$

Watts et al., SMO, 2019.

Simulation of thermal deformations

The inherent strain method is adopted to predict thermal deformations during printing.

– Parts are assumed to be printed in a limited number of stages, each representing the deposition of several layers.
– For each printing stage, inherent strains are applied as initial strains in the newly added layers, and the resulting displacements are calculated by means of the finite element method.
– The appropriate inherent strain values are experimentally determined for a given material, machine, and printing strategy.



Cheng et al., Additive Manufacturing, 2016.

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Simulation of thermal deformations

Example: thermal deformations during the printing of a uniformly supported cantilever structure.

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Formulation of the optimization problem

The optimization problem is formulated as a minimum volume problem subject to displacement constraints:

- The optimization problem is expressed in terms of design variables $\boldsymbol{\rho}$.
- A density filter is used to obtain the densities $\tilde{\boldsymbol{\rho}}$ of the elements representing the homogenized support structure.
- The total volume V of the support structure is minimized.
- For each printing stage i and each output degree of freedom j, the displacement $\mathbf{L}_{i,j}^T \mathbf{u}_i$ is limited to a maximum allowable value $u_{\max}$.

$$
\begin{aligned}
\min_{\boldsymbol{\rho}} : \quad & V = \sum_e v_e \tilde{\rho}_e = \mathbf{v}^T \tilde{\boldsymbol{\rho}} \\
\text{s.t.} : \quad & u_{i,j} = \mathbf{L}_{i,j}^T \mathbf{u}_i \leq u_{\max} \quad \forall i, j \\
& \rho_{\min} \leq \rho_e \leq \rho_{\max} \quad \forall e
\end{aligned}
$$

where $\mathbf{u}_i$ is obtained as the solution of $\mathbf{K}_i(\boldsymbol{\rho})\mathbf{u}_i = \mathbf{F}_i$.

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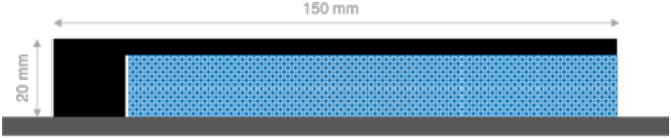
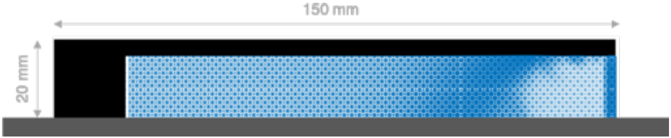
Two-dimensional example



$$V = 16.2\,\% \qquad u_{\max} = 2.13\,\mu\mathrm{m}$$



$$V = 16.2\,\% \qquad u_{\max} = 1.50\,\mu\mathrm{m}$$

Two-dimensional example

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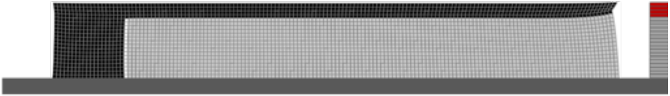
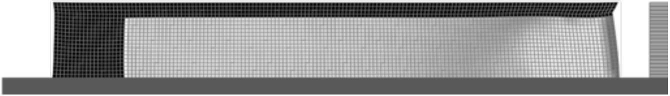
Two-dimensional example

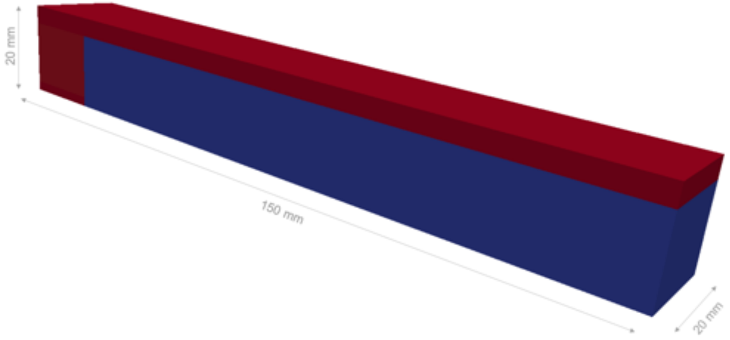


$V = 16.2\,\%$ $\quad u_{\max} = 2.13\,\mu\text{m}$



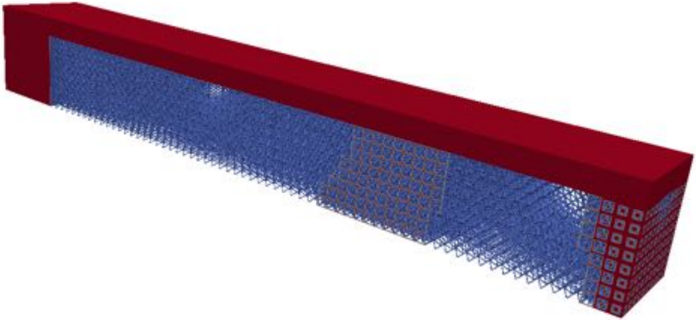
$V = 16.2\,\%$ $\quad u_{\max} = 1.50\,\mu\text{m}$

Three-dimensional example



Three-dimensional example

Three-dimensional example



Conclusion

- Thermal deformations in metal-based additive manufacturing may lead to print failure due to re-coater collisions.
- Sacrificial support structure is added to reduce thermal deformations.
- We developed a numerical optimization approach to design such support structures.
  - → The support structure is modeled as a homogenized lattice structure with the isotruss layout.
  - → Thermal deformations are simulated by means of the inherent strain method.
- Numerical examples show that the resulting support structure successfully reduces thermal deformations using a small amount of material.

J. Pellens, G. Lombaert, M. Michiels, T. Craeghs, and M. Schevenels. Topology optimization of support structure layout in metal-based additive manufacturing accounting for thermal deformations. *Structural and Multidisciplinary Optimization*, 61(6):2291-2303, 2020.