Joint Special Interest Group meeting between euspen and ASPE
Dimensional Accuracy and Surface Finish in Additive Manufacturing,
KU Leuven, BE, October 2017
www.euspen.eu

Controlling Local Overheating in Topology Optimization for Additive Manufacturing

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Abstract

Additive Manufacturing (AM) enables fabrication of geometrically complex designs and hence offers increased freedom for designers. It has been recognized that topology optimization can serve as an ideal design tool in order to fully exploit the advantages offered by AM. However, AM processes have specific limitations which should be taken into account at the design optimization stage in order to minimize manual design adaptations and post processing cost. One such major constraint is local overheating during processing. It is evident that excessive local heating can cause defects such as melt ball formation which subsequently leads to poor surface finish and undesired mechanical properties. The issue becomes even more critical for manufacturing precision components as higher dimensional accuracy and better surface quality are desired in this case. This paper presents a simplified thermal model inspired by the physics of additive processes and detects zones of local heat concentration i.e. `hotspots' in a geometry. Although the model emulates the boundary conditions of an AM layer and predicts the temperature field, it is not a detailed process simulation. Instead, a dedicated computationally inexpensive thermal analysis has been preferred here as it proves to be able to identify regions which are prone to overheating. The model is thus referred to as 'hotspot detector'. A mathematical formulation is developed in order to integrate the 'hotspot detector' model with the density based topology optimization using adjoint sensitivity calculation method. The new method is tested and demonstrated on several numerical examples.

Keywords: Topology Optimization, Additive Manufacturing, Design for Additive Manufacturing (DFAM)

1. Introduction

Additive manufacturing (AM) refers to a collection of manufacturing techniques based on layer by layer material deposition for fabricating 3D geometries. As geometries are manufactured in a layered manner, components with unprecedented geometrical complexities can be fabricated without additional manufacturing cost. Therefore, the main advantage that AM offers is the increase in design freedom compared to conventional subtractive techniques. However, the process is not completely free from manufacturing constraints. Hence, in order to fully capitalize on the benefits offered by AM, a comprehensive understanding and consideration of process constraints is required at the design stage.

In a typical metal AM process, a laser heat source is used to selectively melt a thin layer of powder. The high local heat input causes steep temperature gradients which depend on local geometry and material properties. Design features such as thin sections, acute overhangs etc. cause local overheating which has a detrimental effect on dimensional accuracy and mechanical properties. It has been reported extensively in literature that acute overhangs are particularly difficult to manufacture as they tend to cause excessive local overheating which leads to defects such as melt ball formation and poor surface finish [1][2]. Therefore, minimization of local overheating during the build process of a part is of paramount importance for precision components. However, it is not always possible to avoid all the overhanging features in a design, therefore they are manufactured with supports for proper heat dissipation. These supports are generally sacrificial structures which needs to be removed in the post-processing step which increases overall manufacturing time and cost. Therefore, AM processes are generally reported to have a material specific maximum allowable overhang angle which is determined empirically and should be considered while designing the geometry.

As suggested by Wang et.al. [3], one method to minimize overhang is to select the optimal build orientation. However, this option is not always practical for complex parts. Craeghs et.al. [2] suggested feedback based control of laser parameters for reducing local overheating caused by overhang features. Another method is to incorporate an overhang constraint at the design stage. Multiple authors have approached this as a purely geometrical problem and successfully implemented the constraint within a standard topology optimization (TO) process [4-7]. However, these methods do not address the underlying thermal aspect of the problem and thus do not guarantee avoidance of local overheating issues. Moreover, procedures based on such assumed geometric rules may in fact be overly restrictive and a method more directly linked to the local thermal conditions during the AM process is to be preferred. In this research, we propose a method that accounts for local overheating and integrate it with the standard TO process.

2. Research Methodology

2.1 Hotspot detection

This sections describes the proposed method for detecting zones of local heat accumulation, i.e. 'hot spots' inexpensively in a given geometry. Rationale behind the approach is that local geometry determines whether a given region is prone to overheating. Therefore, a local conductivity test is performed. As a first step, the geometry is decomposed into a number of overlapping slabs. Here, the term 'slab' refers to a set of subsequent AM part layers. In the next step, each slab is subjected to thermal boundary conditions similar to that of a part layer in a typical AM process and temperature information is obtained by performing a thermal FEA. Temperature information from each slab is assembled for the entire geometry by selecting maximum value for each node of the FE mesh and regions with relatively high temperature values are identified as 'hot spots'. Figure 1 presents a schematic of the process in which a wedge shaped geometry with a hole is divided into overlapping slabs and the assembled temperature field shows that the region just above the circular hole is identified as a hotspot.

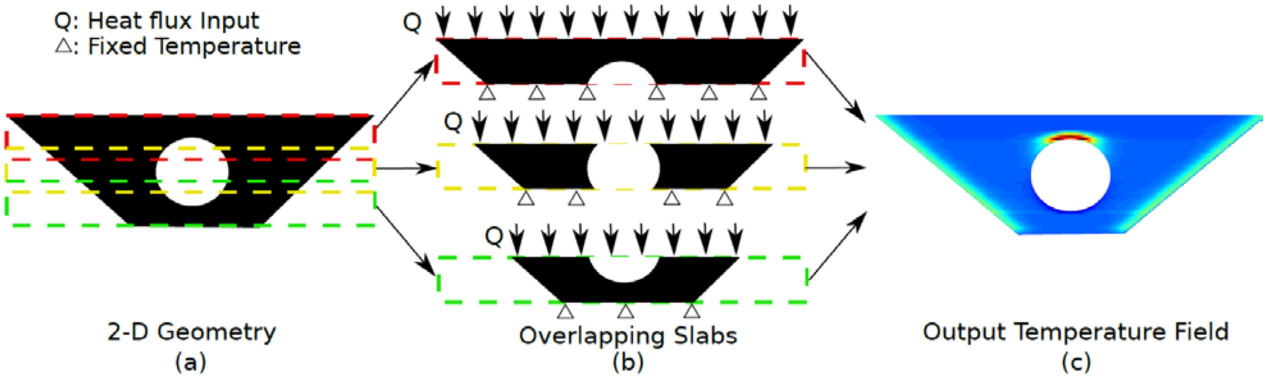

Figure 1. Hot spot detection method: (a) a wedge shaped geometry decomposed into a set of overlapping slabs (b) individual slabs with applied boundary conditions (c) temperature field obtained by assembling temperature information from all the slabs

2.2. Overhang-Temperature correlation

It has been observed that an acute overhang in a geometry causes heat accumulation and use of support structures has been reported in order to facilitate heat flow [1]. In our research, we have found that there exists a correlation between overhang angle and the maximum temperature generated due to the overhang. In order to quantify this correlation, an analytical model using Fourier's law of heat conduction has been developed. The developed analytical model has been validated using the hot spot detection method described in section 2.1.

In order to test the accuracy of the analytical model, geometries with different overhang angles have been constructed and subjected to hotspot detection method. The temperature field obtained is then used for back calculating the overhang angle values using the developed analytical model. It has been found that analytical model is capable of approximating overhang angle values using temperature information. It is also observed that accuracy of the analytical model is relatively better for smaller, i.e. acute overhang angles which are more likely to cause local heat accumulation.

2.3. Integration with Topology Optimization

The hot spot detection scheme is integrated with density based topology optimization (TO) process as a temperature constraint. In each TO design iteration, the hot spot detection algorithm is applied on the entire design domain and temperature information is obtained. An aggregation scheme is then used to specify a maximum allowable hot spot temperature as a constraint. To set the critical temperature, in this study we choose a limiting overhang angle for the AM process on interest and calculate the corresponding maximum allowable temperature using the analytical model described in section 2.2.

The well-known 88 line topology optimization code by [8] has been extended to incorporate hot spot detection. The method of moving asymptotes (MMA) [9] has been used for optimization and sensitivity information has been mathematically computed by the adjoint method and provided to the optimizer.

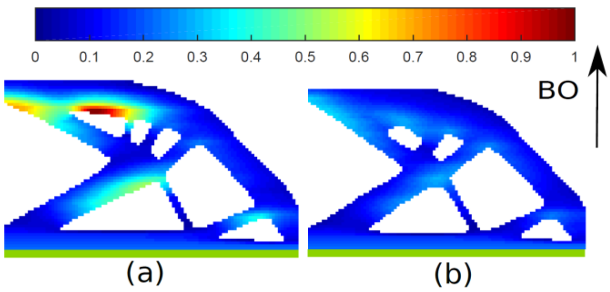

Figure 2. Normalized temperature fields for the designs obtained by (a) Standard TO (b) Hot spot constrained TO

3. Numerical example

The above described method has been applied to a compliance minimization problem for the well-known cantilever loading case. The design domain is discretised into 100x60 square elements and limiting angle of 35° has been used for defining maximum allowable hotspot temperature. Figure 2(a) and (b) presents the designs obtained by standard and thermally constrained TO process respectively. The normalized temperature fields obtained after applying hotspot detection method on the final designs are also superimposed. A reduction of 69% in the maximum hotspot temperature has been achieved with a 4% increase in the objective i.e. compliance. Build orientation (BO) has been marked with an arrow and a green coloured base indicates the substrate plate.

Figure 3(a) and (b) presents overhang angles for the obtained geometries. It is to be noted that large overhangs with angles less than 35° (marked with red colour) are avoided in the hotspot constrained TO. Therefore, we observe that by controlling hotspot temperature, minimum overhang angles are also regulated. This indicates a link between hotspot temperature and overhang angle, although the presented temperature-based approach is less strict than geometry-based methods, and in some smaller regions with sufficient local conductivity violation of set overhangs constraint is allowed.

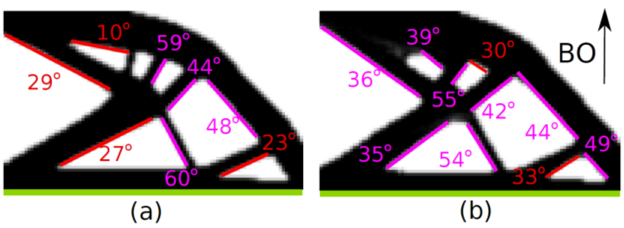

Figure 3. Overhang angles for designs obtained by (a) Standard TO (b) Hot spot constrained TO

4. Summary and Future work

A topology optimization method which incorporates thermal aspect of the AM process has been proposed in this paper. The advantage that this method offers over already existing geometry based approaches is that it incorporates temperature response of a geometry instead of imposing explicit prohibition of overhangs. Therefore, improved surface finish and dimensional accuracy can be achieved by avoiding local overheating while manufacturing designs created by the developed TO method. This is expected to contribute to the application of AM and TO in the precision industry. Next steps include a study to characterize the influence of various TO parameters. The extension of the hot spot detection idea to a 3D TO problem is also an avenue for future research.

Acknowledgement

This work was made within PAM^2 , 'Precision Additive Metal Manufacturing', a research project funded by The EU Framework Programme for Research and Innovation - Horizon 2020 - Grant Agreement No 721383.

References

[1] J.-P. Jrvinen, V. Matilainen, X. Li, H. Piili, A. Salminen, I. Mkel, and O.Nyrhil. Characterization of effect of support structures in laser additive manufacturing of stainless steel. *8th International Conference on Laser Assisted Net Shape Engineering*, LANE. Physics Procedia, **56**:72- 81, 2014.

[2] T. Craeghs, F. Bechmann, S. Berumen, and J.-P. Kruth. Feedback control of Layerwise Laser Melting using optical sensors. *Physics Procedia,* **5**: 505-514, 2010.

[3] D. Wang, Y. Yang, Z. Yi, and X. Su. Research on the fabricating quality optimization of the overhanging surface in slm process. *The Int. J. of Adv. Manuf. Tech.*, **65**(9):1471-1484, 2013.

[4] D. Brackett, I. Ashcroft, R. Hague. Topology optimization for additive manufacturing. In: *Proceedings of the solid freeform fabrication symposium*, Austin, TX, pp 348–362, 2011.

[5] M. Langelaar. An additive manufacturing filter for topology optimization of print-ready designs. *Struct. Multidiscip. O.*, **55**(3): 871-883, 2017.

[6] E. van de Ven, C. Ayas, M. Langelaar, R. Maas, F.V. Keulen. A PDE-based approach to constrain the minimum overhang angle in topology optimization for additive manufacturing. *12th World Congress on Structural and Multidisciplinary Optimization*, Braunschweig, Germany, pp 1-11, 2017.

[7] A.T. Gaynor, J.K. Guest. Topology optimization for additive manufacturing: considering maximum overhang constraint. In: *15th AIAA/ISSMO multidisciplinary analysis and optimization conference*, Atlanta, GA, pp 16–20, 2014.

[8] E. Andreassen, A. Clausen, M. Schevenels, B. S. Lazarov, and O. Sigmund. Efficient topology optimization in matlab using 88 lines of code. *Struct. Multidiscip. O.*, **43**(1):1-16, 2011.

[9] K. Svanberg. The method of moving asymptotes - a new method for structural optimization. *Int. J. Numer. Meth. Eng.*, **24**(2):359–373, 1987.