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Effect of stiffness anisotropy on topology optimisation of additively manufactured structures

Louis N.S. Chiu[a,b], Bernard Rolfe[b], Xinhua Wu[a], Wenyi Yan[c,*]

[a] Department of Materials Science and Engineering, Monash University, Clayton, VIC 3800, Australia
[b] Institute for Frontier Materials, Deakin University, Waurn Ponds, VIC 3216 Australia
[c] Department of Mechanical and Aerospace Engineering, Monash University, Clayton, VIC 3800, Australia

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ABSTRACT

Additive manufacturing has been receiving attention as it is capable of producing complex geometries previously unmanufacturable, particularly those resulting from topology optimisation. However, additive manufacturing processes like Selective Laser Melting result in materials that have varying ratios of anisotropy. Currently, the majority of topology optimisation algorithms utilise an isotropic assumption. Through a case study, the present study confirms the hypothesis that anisotropy in the stiffness of the material has a significant detrimental effect on the optimisation outcome where (1) increasing ratio of anisotropy; and/or (2) increasing deviation of the building angle away from being parallel or perpendicular to the principal loading direction results in the decrease of volume reduction achievable through topology optimisation. Material with an out-of-plane shear modulus which is very different from the "near isotropic" value also performed poorly. Compared with the 50% weight reduction of an isotropic case, the worst anisotropic case only managed approximately 27% weight saving. However, in the cases where both the building angle is small ($< 30^{\circ}$) and the degree of anisotropy is low ($\leq \pm 10\%$), the impact on resultant volume reduction was small ($< 10\%$). This study indicates that, in general, material anisotropy should be considered in topology optimisation for additive manufacturing.

1. Introduction

Additive Manufacturing (AM) has been attracting attention as it substantially increases the range of geometries that can be manufactured. Additive manufacturing makes it possible to manufacture complex geometries created via topology optimisation which cannot be made using traditional techniques. One key advantage is that accessibility constraints or clashes that are present in subtractive processes, due to the size of the tooling and associated spindle, do not apply to additive processes [1]. This increased design space had prompted the development of topology optimisation algorithm with integrated powder removal and build geometry limitation considerations [2–4] to generate geometries with features such as undercuts, enclosed spaces as well as internal voids to achieve weight reduction. In general, these optimised geometries are only producible using AM techniques.

The essential nature of the AM process is the incremental deposition of material, which leads to directionality in the material properties. Selective Laser Melting (SLM) produces material with different strength, modulus and elongation to failure [5–8] between the build direction, which is the layering direction of successive deposits, and the transverse direction, which lies on the plane perpendicular to the build direction. For example, the build direction modulus of a Nickel superalloy, IN738LC, produced using SLM, was 67% of the modulus in the transverse direction [7]; and the build direction modulus of Ti6Al7Nb alloy was 138% of the transverse direction modulus [6]. Due to the dependence of topology optimisation on AM to arrive at the final product, anisotropy in the AM process must be incorporated into the topology optimisation process to make it meaningful in the industrial context. However, most topology optimisation algorithms currently available do not include considerations for anisotropy [9].

Most of the work in topology optimisation focussed on the analysis of isotropic and linearly elastic materials [10–13]. More recently, researchers have looked into more complex material models [14], various failure models [15,16], structure built using multiple materials [17,18] or functionally graded materials [19]. Substantial research had been conducted on "porous anisotropic materials" [20–22], which involved the design of unit cell structures of the lattice through topology optimisation to manipulate the bulk properties of the lattice, as well as the simultaneous optimisation of microscopic orientation and topology [23]. Those works focused on emergent anisotropy due to unit cell

* Corresponding author.
E-mail address: wenyi.yan@monash.edu (W. Yan).

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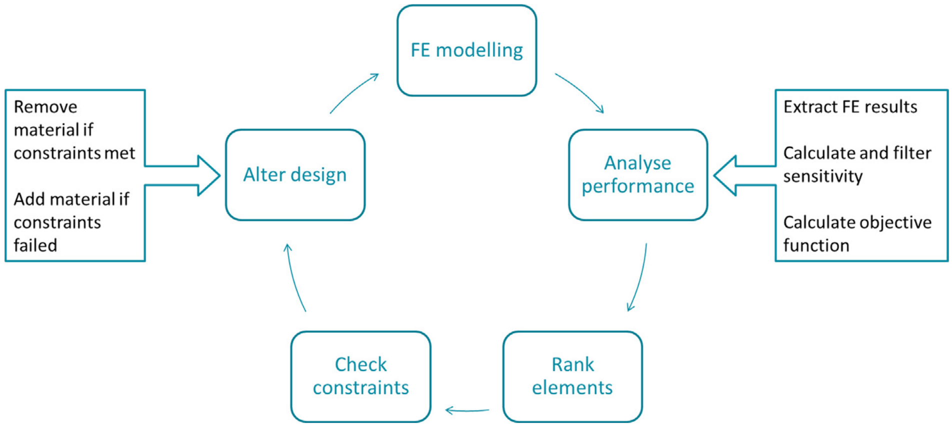

Fig. 1. Flowchart for the BESO method.

shape produced by topology optimisation without considering anisotropy of the underlying material in the analyses.

The deposition process had been studied to understand the role of material anisotropy in the path planning of the deposition process [24] and the authors noted a lack of integration with topology optimisation. Similarly, the optimal distribution of fibre orientation for extruded parts manufactured using injection moulding [25], the optimal configuration of composite laminate structures with angled plies [26], the optimal arrangement of the distribution of material orientation within a structure [27] and the optimal building angle for a given design and load [28,29] had been studied but without simultaneous optimisation of the structural geometry.

The interaction between material anisotropy and build orientation within topology optimisation has not been well studied in the literature. For a level set optimisation algorithm, which is a gradient-based method, the building angle was shown by Liu [30] to affect the optimisation outcome of structures with anisotropic elastic moduli. However, only the shear modulus was varied. The Young's moduli of the build and transverse directions remained identical in Liu's work.

The present work looks at the intrinsic anisotropic nature of the material produced and how the anisotropy in stiffness affects the progression of topology optimisation. The effect of building angle and degree of anisotropy on the outcome of Bidirectional Evolutionary Structural Optimisation (BESO) is explored through a parametric study of a simple test case. Material anisotropy is directly considered in the topology optimisation. In addition, the present study probes the changes in the optimised solution with increasing ratios of anisotropy, informing the design process as well as the material selection process.

2. Methodology and case study

2.1. Topology optimisation using the BESO method

Topology optimisation is a numerical tool to iteratively improve structural designs for a given set of performance requirements and constraint. Evolutionary Structural Optimisation algorithm [31] had later evolved to become Bidirectional Evolutionary Structural Optimisation (BESO) algorithm [32] which is the basis for the present study. This work builds on previous work [2] adapting and implementing the BESO method for practical applications in additive manufacturing beyond the typical stiffness optimisation. This implementation included a continuity constraint [3] which prevented the formation of null solutions where the load is disconnected from the boundary conditions. Considerations for the SLM manufacturing process had also been included [4].

The main driving equations for this algorithm are summarised below. Weight reduction, which is the primary objective of the optimisation process, is achieved through the removal of material from the structure (volume reduction), i.e.:

$$\begin{aligned}&\textit{Minimise } f(\boldsymbol{X}) = V \textit{ where } \boldsymbol{X} = \{x_1,\ldots,x_i,\ldots,x_n\} \in \{0,1\}\\&\textit{subject to constraint conditions}\end{aligned} \tag{1}$$

V is the volume of the part in question and $\boldsymbol{X}$ is the vector of design variables. The constraint conditions ensure that the optimised solution has the same performance as the original. These include a constraint on continuity of material between all boundary conditions to suppress the trivial null solution and a constraint on the maximum stress possible in the design. The ith element (in the discretised optimisation domain containing n elements) is kept if $x_i = 1$ and removed if $x_i = 0$. The elastic strain energy (Eq. (2)), a sensitivity number developed by Chu et al. [33], was used to maximise stiffness of the structure. The sensitivity number was adopted from literature as the current focus is on the effect of anisotropy on the current approach. Future work includes conducting a sensitivity analysis similar to that performed by Huang et al. [18]. The optimisation process is progressed by processing individual elements based on their sensitivity (α_i) which is obtained by applying filters on the raw sensitivity (α_i^{raw}).

$$\alpha_i^{raw} = E_i \tag{2}$$

Elements are ranked in order of sensitivity at each iteration and those that are below a threshold are selected for removal. Constraint conditions are checked at each iteration. The selected elements are removed only if all pre-defined constraint conditions are satisfied. Fig. 1 gives an overview of the operation of the BESO method.

Spatial filtering of sensitivity values assigned to each element is utilised to remediate numerical issues such as checker-boarding and mesh dependency [34]. The filter radius determines the length scale of such a numerical filter. In the element sensitivity module, the volumes (V_i) and raw sensitivities (α_i^{raw}) calculated for elements i surrounding the node j are mapped to node j using:

$$\alpha_j^{node} = \frac{\sum_{i=1}^{n} V_i \alpha_i^{raw}}{\sum_{i=1}^{n} V_i} \tag{3}$$

Then the spatially filtered elemental sensitivity values (Eq. (4)) can be calculated from the distance between the jth node and the ith element (r_{ij}) and the nodal sensitivity value (α_j^{node}). Only nodes within the BESO filter radius of r_f from element i are included.

$$\alpha_i^{k} = \frac{\sum_{j=1}^{n} (r_f - r_{ij}) \alpha_j^{node}}{\sum_{j=1}^{n} (r_f - r_{ij})} \tag{4}$$

An evolutionary history filter (Eq. (5), [34]) was applied to the spatially filtered sensitivity values in order to suppress unstable modes by taking the sensitivity value of the previous iteration ($k-1$) into consideration.