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ScienceDirect
Comput. Methods Appl. Mech. Engrg. 326 (2017) 358–375
Computer methods in applied mechanics and engineering
www.elsevier.com/locate/cma

Minimum compliance topology optimization of shell–infill composites for additive manufacturing

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Received 17 May 2017; received in revised form 7 August 2017; accepted 11 August 2017
Available online 24 August 2017

Highlights

- A novel method for optimizing shell–infill composites for additive manufacturing.
- The solid shell and the non-uniform, porous infill are optimized concurrently.
- The optimized infill spreads within the shell, and follows principal stress directions.
- Non-uniform infill can perform much stiffer than uniform infill.
- The method demonstrates the good scalability of multiple filtering in optimization.

Abstract

Additively manufactured parts are often composed of two sub-structures, a solid shell forming their exterior and a porous infill occupying the interior. To account for this feature this paper presents a novel method for generating simultaneously optimized shell and infill in the context of minimum compliance topology optimization. Our method builds upon two recently developed approaches that extend density-based topology optimization: A coating approach to obtain an optimized shell that is filled uniformly with a prescribed porous base material, and an infill approach which generates optimized, non-uniform infill within a prescribed shell. To evolve the shell and infill concurrently, our formulation assigns two sets of design variables: One set defines the base and the coating, while the other set defines the infill structures. The resulting intermediate density distributions are unified by a material interpolation model into a physical density field, upon which the compliance is minimized. Enhanced by an adapted robust formulation for controlling the minimum length scale of the base, our method generates optimized shell–infill composites suitable for additive manufacturing. We demonstrate the effectiveness of the proposed method on numerical examples, and analyse the influence of different design specifications.

Keywords: Topology optimization; Additive manufacturing; Two-scale structure; Infill; Coating; Composite

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http://dx.doi.org/10.1016/j.cma.2017.08.018
0045-7825/

1. Introduction

Topology optimization has been recognized as an important design method for additive manufacturing, as it fully leverages the manufacturing flexibility enabled by the layer-upon-layer additive process. It finds an optimized material distribution in the design space to maximize the structural performance under given boundary conditions and constraints [1]. Early works in topology optimization are summarized in the book [2], and recent developments until 2013 are reviewed in [3,4].

While topology optimized material distributions mostly represent solid models, engineering practices in additive manufacturing seem to favour porous structures [5,6]. In fused deposition modeling (FDM), a commonly used additive manufacturing technology, the interior of 3D models is often represented by repetitive infill patterns (e.g., triangles and hexagons). The porous infill is introduced to control the cost associated with material usage and printing time. The shell–infill composite involves a few parameters, including the shell thickness, infill pattern, and infill volume percentage. These parameters are specified by designers to roughly balance cost and mechanical properties. In general a larger shell thickness and a larger infill volume percentage lead to a stronger print, while consuming more material and prolonging the printing time.

Our current research is motivated from two perspectives. First, post-processing topologically optimized solids into shell–infill composites guarantees no optimality on the final structure, thereby wasting the efforts of the sophisticated numerical optimization. It is thus of high interest to consider such a shell–infill composite directly in the structural optimization routine, eliminating the conversion from optimized solids to sub-optimal shell–infill composites. Second, shell–infill composites can obtain significantly increased stability with respect to buckling [7] and unpredicted loading conditions [8] at the expense of a minor increase in compliance. Given the manufacturing flexibility enabled by additive manufacturing, such two-scale structures have a high potential to be widely employed in industrial metal printing (e.g., using selective laser melting).

Two recent developments (partially) address the optimal design of shell–infill composites by extending density-based topology optimization known as SIMP (Solid Isotropic Material with Penalization) [9]. These two extensions are complementary in the sense that they optimize one component in the composite, i.e., shell or infill, while assuming the other component prescribed. Specifically, Clausen et al. [10,11] proposed a method to design coated structures, i.e., a composition of a solid shell and base material. The base material can be interpreted as a uniform infill, with a homogenized stiffness smaller than the stiffness of the solid coating material. The coating-base structure is obtained by introducing a two-step filtering process to separate the base and the coating from a scalar field of design variables. Conversely, to optimize infill within a prescribed shell, Wu et al. [8] presented a method to design bone-inspired micro-structures as porous infill. This is achieved by introducing an upper bound on a local volume measure, in order to regulate the local material distribution. The idea of local upper bounds is similar to maximum length scale [12,13]. The resulting porous infill is dominated by crossing sub-structures, distributed in the entire space enclosed by the prescribed solid shell, and following principal stress directions. The optimized infill performs much stiffer under given boundary conditions than the commonly used, uniformly repetitive infill patterns.

This paper moves a step further and presents a complete solution to the optimal design of shell–infill composites by concurrently evolving the shell interface and the micro-structural infill. In particular, we propose a novel formulation to consider both the coating-base and infill constraints in density-based topology optimization. Two design fields are utilized to respectively derive the coating-base distribution and the infill distribution. The intermediate distributions are unified by a material interpolation scheme into the final physical density field, based on which the compliance is minimized. Furthermore, the robust formulation [14] is adapted to ensure length scale in the composite, leading to distinct infills.

The design of shell–infill composites is among recent developments addressing geometric constraints for additive manufacturing. Langelaar [15], Qian [16], and Gaynor and Guest [17] proposed methods to ensure the property of self-support in optimized structures. Such methods follow the filtering scheme proposed by Guest et al. [18] and extended in [19,12,20] which are also the basis of our current work. Wu et al. [21] proposed a rhombic pattern as a special self-support infill, and performed infill optimization by adaptively subdividing the rhombic cells. The length scale problem relevant to manufacturing technologies in general is thoroughly examined by Lazarov and Wang in [22]. Our method involves and justifies the use of multiple filtering steps (four smoothing steps and three projections in particular), in addition to the interpolation of two design fields and a gradient norm operator. Arguably, it sets a new extreme with respect to the number of the involved filtering operations — The most complicated combo of filters so far seems to be the four successive filters for the open-close operation suggested in [19]. Here the four filtering steps