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Topology optimization for functionally graded cellular composites with metamaterials by level sets

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Abstract

The application of auxetic composites in practice often relies on a compromise between properties as auxetics are mostly too porous (not dense enough or not stiff enough) to bear structural loads. Hence, the focus of this paper is topological design optimization of new functionally graded cellular composites with auxetics using a level set method. Firstly, a new hierarchical multi-scale formulation is developed to account for both the auxetic behavior of the microstructure and the stiffness of the macrostructure. The composite, comprising multiple layers of periodic microstructures, is tailored to have functionally graded properties for stiffness and auxetic behaviors, subject to volumetric gradient constraints. Secondly, the microstructures underpinning composite layers are topologically designed under the consideration of boundary and loading conditions of the macrostructure. Finally, a level set method is applied to evolve the shape and topology of the microstructure for each layer, with the numerical homogenization method to evaluate the effective properties of the microstructures. Several numerical examples are used to demonstrate the effectiveness of the proposed method. It can be seen that such composites systematically gear together the features of the functionally graded materials, cellular composites, and metamaterials towards a new kind of man-made composites.

Keywords: Topology optimization; Level set method; Functionally graded materials (FGMs); Cellular composites; Auxetic metamaterials

1. Introduction

Metamaterials are artificially designed composites engineered to have unusual properties that are difficult to find in nature [1,2]. Auxetic metamaterials are a special class of elastic materials that exhibit negative Poisson's ratio (NPR) [3,4]. In contrast to most conventional materials with positive Poisson's ratios, auxetic materials contract in transverse directions when they are compressed uniaxially. In traditional auxetics, the phenomena of negative Poisson's ratio is associated with specific mechanisms of microstructural deformation which allows rotating effects, e.g. re-entrant, chiral and rotating-units structures [5]. Auxetic metamaterials can find a wide range of applications,

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e.g. energy absorption, anti-impact, indent resistance, thermal isolation, fracture toughness, acoustic and vibration dampeners, biomedical applications [6,7]. However, one of the main limitations of most current NPR composites [8,9] in practice lies in their lower stiffness under in-plane compression.

The concept of multifunctional cellular composites has grown rapidly in importance in engineering [10,11]. These porous materials are always characterized with lightweight but high performance. Moreover, cellular composites are flexible in tailoring specific effective properties by modifying their microscopic configurations rather than the constituent materials [12]. Particularly, periodic cellular composites consist of a number of identical microstructures configured in the design space. Hence, the layout of material distribution inside a microstructure provides potential to create cellular composites with multiple functions by using advanced design techniques, such as topology optimization [13,14]. For instance, with the numerical homogenization method [13,14] to predict the effective properties of a microstructure, topology optimization has been used to design NPR microstructures fashioned from conventional materials, e.g. [14–16]. Unfortunately, it can be found that the above studies are mainly focused on the property of NPRs, and the property of the macro structure is seldom included in the design.

Functionally graded materials (FGM) are recognized as a kind of inhomogeneous materials, engineered to have gradient properties by progressively changing the compositions or microstructures over the volume. Studies [17–19] reveal that the biological structures (e.g. bamboo, shell, tooth, bone, etc.) change their mechanical properties layer by layer by varying the constituent materials in order to adapt to environmental stimuli, which can be regarded as the origin of the concept of FGM. This implies that the FGMs can be adapted to loading and boundary conditions defined by their service environments in order to improve the mechanical performance, e.g. stiffness, strength and toughness. Inspired by the natural FGMs, engineers start to generate materials with graded properties and multiple functionality for industrial applications, e.g. aerospace and vehicle engineering [20–22]. Hence, we can see that the key concept of FGMs is the incorporation of the multiple functions of different material compositions or microstructures. In practice, the advanced manufacturing in engineering, such as the current additive manufacturing (AM) techniques, will facilitate the application of the man-made FGMs. However, how to achieve FGM properties through the change of material constituents or microstructures over volume is always challenging.

Recently, there is a tendency in implementing man-made FGMs with microstructures by using the topology optimization method [23–26]. In these papers, the numerical homogenization method has been widely used to evaluate the effective FGM properties, when the material properties are subject to small variations [23,24]. The connectivity issue between adjacent microstructures along the gradient direction of the FGMs has also been widely studied. For instance, Zhou and Li [25] proposed three different approaches to maintain the connectivity between adjacent periodic base cells of the FGMs. Radman et al. [26] developed an efficient method to design the FGMs, in which every three base cells were devised simultaneously and a filtering scheme was performed to preserve the connectivity of the FGMs. However, most of the current works only focused on the single scale design of the FGM microstructures. In engineering, the effect of loading and boundary conditions of the macrostructure upon the microstructure [27–32] should also come into the picture in the topological design of FGMs.

Topology optimization has been recognized as an effective computational design tool for a diversity of structural and material applications [33]. It is a numerical iterative procedure that topologically changes the geometry of the structure within a given design domain subject to boundary conditions until the objective function is optimized. So far, several different methods have been developed for topology optimization, such as the homogenization method [34–36], the solid isotropic material with penalization (SIMP) method [37,38], the evolutionary structural optimization (ESO) method [39] and the level set methods (LSM) [40–43]. One of the most promising applications of topology optimization is the synthetic design of material microstructures.

The numerical homogenization method has been widely applied to topology optimization for inverse design of various material microstructures [13–16,44–51]. The numerical homogenization method [13,14] is often used to evaluate the effective properties of the microstructures, and topology optimization methods are applied to determine the topologies of the microstructures. Then the composite material is formulated by periodically configuring a number of microstructures under the assumption that the geometrical sizes of the microstructures are much smaller than that of the macrostructure. Many topological design methods have been developed to create microstructures with extreme or expected properties [13–16,44–51]. However, most of the above designs are based on the material density distribution methods, e.g. [13–15,44–50].

LSM [40,41] have been used as an alternative method for structural shape and topology optimization design problems [42,43,52–58]. The key concept of LSMs is to represent the design boundary of a structure as the zero