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A level set method for shape and topology optimization of coated structures

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Highlights

- We consider topology optimization of bi-material coated structure using level set method.
- Only one level set function is needed to represent structure with uniform coating layer.
- Topology and coating thickness can be exactly described owing to signed distance property.
- Direct relation between level set and coating geometry facilitates sensitivity analysis.
- Effectiveness of proposed method is demonstrated by 2D and 3D examples.

Abstract

Coated structures are commonly used in engineering. The coating material covers the surface of the substrate for protection or to improve certain functionalities. The rising of novel manufacture techniques enables higher design flexibility for such coated structures. This paper presents a level set-based topology optimization method for the design of structures with coating layers. Though a coated structure is composed of two-phase materials, only one level set function is needed in the special case of coating with uniform thickness to describe the distribution of the substrate and the coating layer, thanks to its signed distance property. Without using any intermediate design variables, the proposed method provides a direct interface description between different material phases and geometrical information regarding the coating layer thickness, thus facilitating the sensitivity analysis and numerical implementation. Numerical examples show that the method can be applied to both 2D and 3D problems.

Keywords: Topology optimization; Level set; Coated structure; Material interface

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1. Introduction

Since the pioneering work of Bendsøe and Kikuchi [1], topology optimization has achieved considerable success and become a powerful tool in academic researches and engineering applications [2–5]. As a popular shape and topology optimization method, the level set method has gained great development [6]. It was introduced into structural

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optimization by Sethian and Wiegmann [7], Wang et al. [8] and Allaire et al. [9], since then some variations, including the color level set method [10], the parametrical level set method [11], and the fictitious interface energy method [12], have also been proposed.

For multi-material structures, Luo et al. [13] presented a piecewise constant level set method, in which a single "indicator function" is used to identify all material phases. Tavakoli [14] proposed a method based on the Ginzburg–Landau energy functional, which combines the SIMP scheme and the phase field model. In both methods, an additional constraint is required to avoid overlap between different material phases. Wang et al. [15] proposed a Multi-Material Level Set (MM-LS) model, in which m level set functions are employed to represent $m + 1$ phases without redundant ones. A similar model has also been used by Liu et al. [16] in the layout optimization of structures considering cohesive material interfaces.

To facilitate manufacturing of the optimized structures, incorporating various manufacturing constraints directly into topology optimization has drawn increasing attention. Guest et al. [17] proposed a Heaviside projection method for minimum length scale control of structural members. In the level set framework, Luo et al. [18] introduced a quadratic energy functional to control the structural member widths in the shape and topology optimization of compliant mechanisms. Xia and Shi [19] imposed a constraint on the distance from the boundary to the skeleton to control the length scale. Also using the level set method, Allaire et al. [20] and Wang et al. [21] achieved thickness control based on the offset of structural boundaries. Allaire et al. [22] then extended this strategy to the topological design of cast parts. Xia et al. [23] suggested a molding condition to insure satisfaction of the casting requirement by restricting the level set velocity along the parting direction. Li et al. [24] proposed a level set method for 3D structural optimization with extrusion constraints by using a cross section projection strategy. Zhu et al. [25] considered the integrated layout design of multi-component system. The so-called finite circle method (FCM) was used to avoid component overlaps. The method has been extended to a variety of design problems involving multi-components [26,27]. Kang and Wang [28] studied topology optimization of structures with embedded movable holes and components. They used the level set model to describe the component layout and the independent point-wise density interpolation method (iPDI) [29] to represent the main structural topology, and proposed an explicit integral-type non-overlap condition to avoid overlap of the embedded components. Later, the integral-type condition expressed with the level set function was extended to the topology optimization with minimum distance control of multi-material embedded components [30].

The topological design of so-called coated structures presents a special restriction on the design space, which can also be regarded as a manufacturing constraint. Conventionally, coating treatment is employed to protect the substrate structure from severe working conditions (*e.g.* extreme temperature or corrosive environment), or to improve certain functional properties [31]. In some new industry applications, coating has also become a useful technology for implementing novel structural concepts. For example, with the help of the coating technology, a type of ultralight metallic material, constructed from a micro-lattice of nickel phosphorous tubes that is 99.9% air (Fig. 1(a)), was presented in 2011 [32]. This material is fabricated by starting with a "prototyping template", coating the template by electroless nickel plating, and subsequently etching away the template. Particularly, the coating technology also provides a way to combine the merits of both the coating and substrate material properties. For instance, coating polymer structures with metal combines the cost-effectiveness of processing complex-shaped polymer substrate and the excellent mechanical property of metals. Some bone-like structures [35] and hollow-shell structures (see Fig. 1(b)) can also be considered as coated structures. During the last decades, studies on the bioceramic coating, which is extensively applied in medical implants, has emerged as a hot topic among material scientists [36].

The fast development of fabrication technology offers new possibility for manufacturing of coated structures. A typical coated structural configuration consists of an inner part of porous infill and an exterior solid shell to act as a main load-bearing part. One example is the world's first 3D-printed patient specific jaw replacement with a bioceramic coating, which was successfully fabricated and implanted in 2012 [34] (Fig. 1(c)).

Despite wide application of coated structures, there are only very limited studies on topology optimization of such structures. An inspiring work we mention here is Clausen et al. [37], which used the Solid Isotropic Material with Penalization (SIMP) method [4] to achieve the minimum compliance topology optimization of coated structures. A series of filtering, projection and gradient norm approaches were introduced to model the coating layer of uniform thickness on the substrate surface. Later, the same authors conducted an experimental study and showed that the coating approach they proposed improved the buckling behavior [38].