Computer-Aided Design 94 (2018) 28–40

Contents lists available at ScienceDirect

Computer-Aided Design

journal homepage: www.elsevier.com/locate/cad

Topology optimization design of cast parts based on virtual temperature method

Quhao Li, Wenjiong Chen, Shutian Liu *, Huiru Fan

State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Dalian, 116024, China

ARTICLE INFO

Article history:
Received 16 January 2017
Accepted 15 August 2017

Keywords:
Topology optimization
Virtual temperature method
Molding constraint
Parting direction
Finite volume method

ABSTRACT

Topology optimization has been widely used in industry for its powerful innovation ability to obtain the concept designs, which are generally unintuitive. But due to the limitation of the manufacturing processes or costs, some of these designs cannot be manufactured directly, so considering manufacturing process constraints in topology optimization becomes increasingly important. This paper presents a new method for structural topology optimization design considering the molding constraint which requires the absence of interior voids and undercuts in the cast parts. A virtual thermal diffusion problem is appropriately defined and a global thermal constraint is added into the optimization model to guarantee the cast-ability of the structural shape. The parting directions, unidirectional or multi-directional, are modeled by modifying heat dissipation boundaries and material properties. This method does not require an optimization process to start from a feasible initialization and can be applied to almost any topology optimization problems. Finite volume method is used to solve a steady-state heat equation and a parametric formulation of the conductive coefficient is given. Several examples of topology optimization of cast parts are provided to illustrate the validity and the effectiveness of the proposed method.

1. Introduction

Topology optimization, as one of the most generic types of optimization techniques, has been used to improve designs through variation of their geometrical and material properties with regard to a set of prescribed objectives and constraints [1]. It does not require a pre-established design and is capable of providing some new, sometimes unanticipated, design ideas for designers. Over the past 30 years, many different topology optimization approaches have been developed [2–4], and these methods have been successfully used for structural design in fields like automotive, aerospace, pharmacology and so on [5–10]. However, topology optimized designs are often too complex to be manufactured, engineers need to modify the designs to accommodate the manufacturing limitations, and it brings a question if this modified design is still an optimal design [11]. In order to address this question, manufacturing constraints should be considered directly into optimization models.

Length scale control and manufacturing process constraints are two significant areas of study which include managing issues of structural manufacturability in order to obtain manufacturable topology-optimized designs [12,13]. A large amount of effort has been devoted to the issue of length scale control in topology optimization, including minimum length scale control of each material phase in the density-based topology optimization schemes [14–18] or the level-set based topology optimization schemes [19–24], maximum length scale control [25], fabrication tolerance during manufacturing [26–28] and so on. For each different manufacturing process, different manufacturing constraints must be considered, so it is difficult to establish a general method to describe the existing manufacturing constraints in all manufacturing processes. In automotive, aerospace and civil engineering manufacturing, casting processes are widely used to produce structural parts by pouring liquid materials into molds, which contain a hollow cavity which produces the desired shape after being allowed to solidify [29]. Unfortunately, most topology optimization design results are too complex to be manufactured via a casting process, so considering molding constraints directly into optimization models in order to produce cast-able designs becomes important. This requirement motivates the presented work.

Different types of casting (metal casting, sand casting, investment casting, etc.) present different constraints on the casting process. In this paper, we confine ourselves to the permanent mold casting, whereby casting molds should be removable after solidification without causing damage to the casting parts or the mold tools. Avoiding this damage puts "molding constraints" on the part's manufacturing process and the original cast design. Directions for how casting molds are to be removed are called the removal directions or parting directions. Xia [30] made a summary

* Corresponding author.
E-mail address: stliu@dlut.edu.cn (S. Liu).

http://dx.doi.org/10.1016/j.cad.2017.08.002
0010-4485/

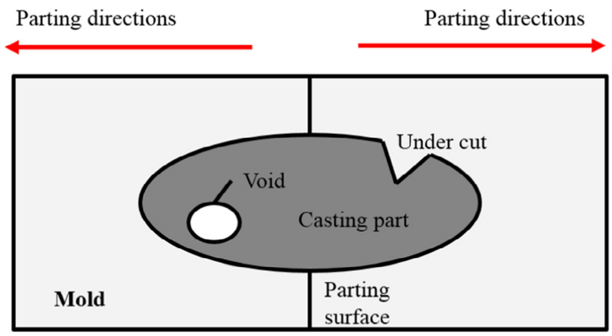

Fig. 1. Illustration of the two conditions under which the molds cannot be removed without damage.

of the molding design constraints stating that cast parts' geometry should not be concave (undercut) and cast parts should not have any interior voids. Fig. 1 presents an illustration of these two conditions under which the molds cannot be removed without damage.

Efforts have been made to incorporate molding constraints into topology optimization models. Zhou et al. [31] first proposed a mathematical formulation of molding constraint in density-based topology optimization schemes which can be summarized as: densities of the elements along in the parting direction cannot decrease. In this method, a variety of linear constraints are introduced into topology optimization models and should be dealt with carefully. Harzheim and Graf [32] successfully incorporated molding constraints into topology optimization based on CAO and SKO methods into TopShape software. Gersborg et al. [33] proposed an explicit parameterization, based on the Heaviside function, to describe the molding constraint. The basic idea of the parameterization is to represent the densities in a row of elements by a single design value controlling the position of the interface between the solid and void. Zhu et al. [34] applied this method in the design of an aircraft skin stretch-forming. Liu et al. [35] extended this method for the design of the layout of stiffened plates with vertically-walled stiffeners of variable heights manufactured using a casting process. Lu and Chen [36] expanded the mathematical formulation proposed by Zhou [31] to describe the multi-directional molding constraint. Projection-based algorithms have been utilized by Guest et al. [37] for imposing the molding constraint on topology-optimized designs. Xia et al. [30,38] proposed a level set based method that transformed the molding constraint into a constraint of the design velocity vector. Allaire et al. [39] and Wang et al. [40] modified this method to a pointwise constraint or a domain integration constraint to avoid the need for feasible initializations. Yamada et al. [41] proposed a topology optimization method using the level set method in which a fictitious interface energy derived from the phase field method is incorporated to consider the uniform-cross section constraint. Li et al. [42] proposed a level set method for topological shape optimization of the 3D structures considering extrusion constraints. Vatanabe et al. [43] proposed a unified projection technique combined with mapping techniques to apply different kinds of manufacturing constraints in the topology optimization. These methods tried to transform the molding constraint to a parametric or projection formulation without establishing a constraint formulation which is more general for all types of optimization problems.

The authors [44,45] have proposed a new model, labeled as virtual temperature method (VTM), for describing and enforcing the desired connectivity constraint in topology optimization. In this paper, this method is introduced and modified to handle the molding constraint in order to guarantee the cast-ability of topologically designed structures. In the modified method, a new virtual thermal diffusion problem is defined and the molding constraint is set to a maximum temperature constraint. The parting directions, unidirectional or multi-directional, are modeled by modifying the heat dissipation boundaries and the material properties. Furthermore, the finite volume method, instead of the finite element method, is used to solve the steady-state heat equation. The compliance topology optimization problem is considered in this paper, but other objective or multi-objective oriented topology optimization problems can also be solved by the proposed method.

This paper is organized as follows. In Section 2, the new equivalent description of molding constraint is presented. Formulations of the density-based topology optimization problem are given in Section 3 and the sensitivity analyses are derived in Section 4. In Section 5, a flowchart of the new method is laid out. In Section 6, representative examples that illustrate the effectiveness of the proposed approach are demonstrated. Lastly, the conclusions are presented.

2. Virtual temperature method for molding constraint

With the virtual temperature (VT) method [44,45], a special temperature model is introduced and the connectivity constraint is converted to an equivalent maximum temperature constraint. This section proposes a modified VT method for establishing the mathematical formulation of the molding constraint including unidirectional and multi-directional molding constraints.

2.1. Formulation of the unidirectional molding constraint

For a cast-able structure, concave boundaries (undercuts) and interior voids should be avoided for the successful removal of molds without destroying either the part's structure or the mold itself. In Fig. 2, three possible structures are depicted; (a) with an interior void, (b) with a concave boundary and (c) a structure without either flaw. For the voids in each structure (as shown in Fig. 2), we assume a virtual unidirectional high heat conductive material and spontaneous heating (regarded as a heat source), whereas the solid areas are filled with a different virtual thermal insulation material. The unidirectional high heat conductive material is assumed to transmit the heat in the parting direction. Here we take the parting direction along the negative vertical direction as an example. Therefore, the bottom boundary of the structure is set as heat dissipation boundary and the other three boundaries are set as heat insulation boundary. The characteristics of the modified VT model for molding constraint are listed in Table 1.

For the structures with an enclosed void (Fig. 2(a)) or concave boundary (Fig. 2(b)), the heat energy generated in the voids cannot be transmitted to the heat dissipation boundary (with $T = 0$), which in turn makes the maximum temperature in the structure relatively high. In contrast, the cast-able structure with a non-concave boundary and no interior voids (Fig. 2(c)) exhibits a satisfactory heat diffusing capability and leads to a relatively low maximum temperature in the structure. So, a structure with the interior voids or the concave boundaries has a relatively high maximum temperature comparing to the cast-able structure. Thus, the maximum temperature value of the virtual steady temperature model can be used as a criterion to determine the cast-ability of a structure. Therefore, the molding constraint, which avoids enclosed voids and under-cuts, can be equivalent to a maximum temperature constraint and formulated as

$$\overline{T}_{\max}\left(k_p, k_v, Q\right) \leq \overline{T}, \tag{1}$$

where $\overline{T}_{\max}$ is the maximum temperature value for the special steady virtual temperature field and $\overline{T}$ is a small number representing the threshold of the required temperature; k_p and k_v are