THE CONCURRENT DESIGN OF MATERIALS AND STRUCTURES FOR CELLULAR MATERIALS ON EFFICIENCY OF HEAT DISSIPATION

Wang Bo, Cheng G.D.

Research Institute of Engineering Mechanics, Dalian University of Technology, Dalian 116023, PR China

<u>*Summary*</u> This paper describes an analytical model for heat transfer of cellular materials and presents a topology optimization method for optimal design of increasing its efficiency of heat dissipation per unit pumping power. Two classes of design variables, volume density and local aperture, are applied not only to optimize macro material distribution as well as the local material topology, so-called concurrent design, but also to avoid confused interpretation for the checkerboard patterns.

INTRODUCTION

It is expected that the function of materials would be applied as efficiently as possibly. However, how to define the so-called efficiency? As a rule, there are two methods. One is to reduce the volume of material as well as gain the indispensable function of structure; the other is to increase the expectation of function while the volume of material is given. All the mentioned above is referred to as light-efficiency. Two groups of researchers, material and mechanical, attain the aim of the game in different pathway that the former is a material design and the latter is a structural design. For example, the team of ultralight metal structures that leaded by Prof. A.G. Evans of Harvard, Prof. M.F. Ashby of Cambridge and Prof. L.J. Gibson of MIT presents several processes of investigation of truss-like materials[1] [2], which are typical material design. In these processes, a discretional local of structure is chose to investigate, which is means that every part of the structure is the same like the local, thus, the contribution of the structural topology for the function is neglected obviously. Topology optimization of two-dimension continuum structures was introduced in the literature by a very significant paper by Bendsøe and Kikuchi[3]. Over the last decade, the researchers have been mainly occupied with two different kinds of topology design processes: the Material or Microstructure Technique and the Geometrical or Macrostructure Technique, which discussed by Eschenauer and Olhoff[4]. The former is a material design because its design domain is a discretional cell just like the material researchers do (Sigmund, Torquato[5]), whereas the latter is a structural design, for the design domain is the structure, which would reduce the weight of structure obviously (Beckers[6], Diaz[7]). It is well known that all the formulations of topology optimization technique are based on the assumption of the material models, such as Hole-in-cell microstructure model and SIMP model. Moreover, the interpretation of intermediate "grey" density of material is often questioned for such models. So suspicion for these models crept into our minds, although Bendsøe and Sigmund can interpret black-white designs in many cases via micro mechanical model[8]. After all, any type of present topology optimization technique does not apply a kind of true models, and too refined micro mechanical models are unpractical for manufacture. In this paper, a true cellular material model based on the efficiency of heat dissipation is applied in the formulation of topology optimization. Since 1980, the cellular material, as a kind of lightweight materials, has been studied for the combinations of mechanical, thermal, acoustic and impact-absorb properties by more and more researchers. Lu.T.J. investigated a sandwich panels with two-dimensional metal cores that be used to carry structural load as well as dissipate heat trough solid conduction and forced convection[9] [10]. As the conclusion, regular hexagonal cores are found to provide the highest levels of heat dissipation. But it is impossible that to obtain the most optimal design by Lu.T.J's method just because the method is a material design mentioned above. In this work we employ numerical techniques for heat dissipation optimization design for two-dimensional cellular structures, which is a concurrent design of materials and structures.

PROBLEM DESCRIPTION

The prototype problem considered is shown in Fig. 1, where the cooling of structure is enhanced by forced convective flow across the honeycomb medium constrained by cylindrical surface Γ of length L. Each element i is all arranged such regular hexagonal cells which axial direction are parallel to the axial direction of cylindrical surface Γ and the direction of cooling fluid passes along. In this paper, our goal is to provide a numerical process (FEM) to discover arrangements of cells for the cross-section of the structure, a 2-dimisional design domain, that optimize the heat dissipate performance at minimum weight. For each element, cell wall length l_i and thickness t_i are showed in Fig. 1. The material topology of each element could be described by two indispensable variables, volume density ρ_i and local aperture a_i.

Fig. 1 notations for physics model and cells of element

where $l_i = (a_i + t_i)/\sqrt{3}$ and $\rho_i = \dfrac{l_i^2 - a_i^2/3}{l_i^2} = 1 - \left(\dfrac{a_i}{a_i + t_i}\right)^2$.
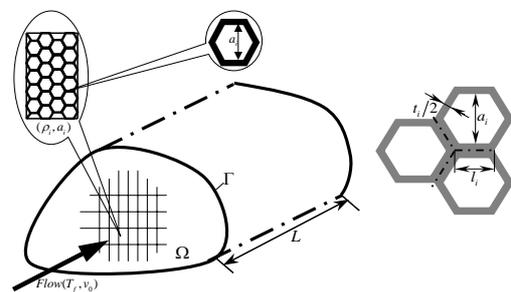
OPTIMIZATION MODEL

Objective function

The heat dissipation performance of the structure is commonly gauged by the ratio of total heat dissipated from the structure Q to the pumping power needed to force the fluid through ΔP. In this work, the objective function, the ratio is referred to as $-\Psi$, the higher this ratio, the better the structure performance.

Constraints

A typical constraint in structure optimization problems is a volume constraint. The allowable volume is denoted by V. The design variable ρ_i has upper bound of one while the lower bound is $\underline{\rho}$ determined by manufacturing criteria of cellular material, which values is 0.03 in this paper. Similarly, the other design variable a_i also has upper bound, $\overline{a}$, and lower bound, $\underline{a}$, with $\underline{a} = 0.5mm$

$$\underset{\rho,a \in V}{Min} \quad \Psi = -\frac{Q}{\Delta P}$$

$$S.t \quad K_T(\rho_i, a_i)T = R(\rho_i, a_i)$$

$$\int_\Omega \rho_i d\Omega = V$$

$$a_i(\frac{1}{\sqrt{1-\rho_i}} - 1) \geq \underline{t}$$

$$a_i \leq \frac{1}{\sqrt{H}}\sqrt{\frac{2}{\sqrt{3}}}\sqrt{s_i(1-\rho_i)}$$

$$0 < \underline{\rho} \leq \rho_i \leq 1 \quad \underline{a} \leq a_i \leq \overline{a}$$

and $\overline{a} = 15mm$ in this work. Banhart John[11] described in detail these manufacturing parameters mentioned above. The parameter of t_i denotes the thickness of cell by Fig.2. Obviously, there should be a lower bound $\underline{t}$ to be applied for it, and $\underline{t} = 0.5mm$ in this work. Otherwise, there should be indispensable number of cells in one element in order to ensure the validity and stability of algorithm. The number is referred to as H, with $H = 1 \sim 4$ in this work, and in the model, s_i is an area of each element. The constraint equation, $K_T(\rho_i, a_i)T = R(\rho_i, a_i)$, denotes the thermal analysis.

NUMERICAL EXAMPLES

In order to improve the effective of heat dissipation of cellular material, it has tendency that the bigger density and smaller aperture foam are arranged in the domain of big temperature grads, while the smaller density and bigger aperture foam are arranged in the others. The smallest average temperature grads for the temperature field are gained for the final optimized material distribution.
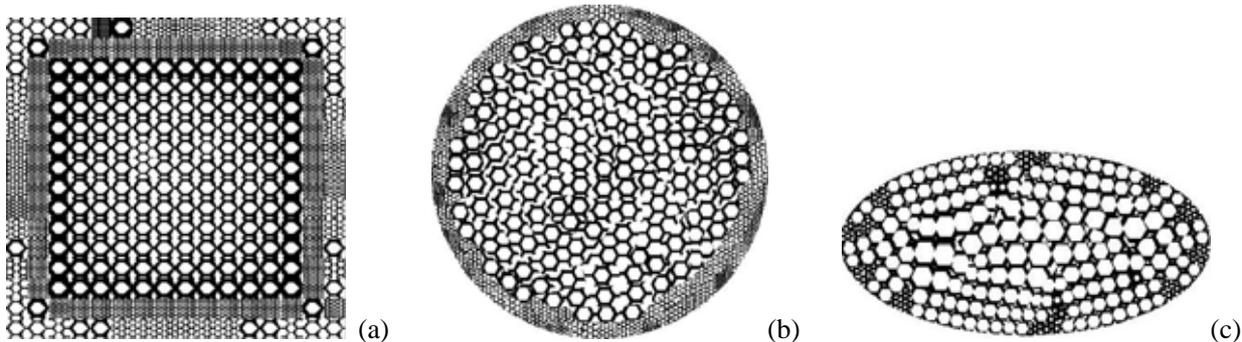

(a)　　　　(b)　　　　(c)

Fig.2 the materials distribution for three kinds of cross-sections: the uniform properties of each example are given to be $v_0 = 10m/s$, $T_f = 283K(10°C)$, $\rho_f = 1.247kg/m^3$, $L = 1m$ and $\mu_f = 14.16E-6m^2/s$. The thermal conductivity are given, $k_s = 200W/m \cdot K$ and $k_f = 0.02W/m \cdot K$. All the boundaries are maintained at constant temperature of $800K$ $(527°C)$. The volumes of material are all 0.4.SLP (Sequential Linear Programming) scheme is applied for all examples: a a quadrate cross-section $0.4m \times 0.4m$ in size; (b) a circle cross-section as the diameter is $0.4m$; (c) a ellipse cross-section as the length of major axis is $0.2m$ and length of minor axis is $0.1m$

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