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Topology optimization of conduction path in laminated metals composite materials

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ABSTRACT

A topology optimization method that can be used to optimize the conduction path in laminated metallic materials between unequal isothermal surfaces is proposed in this study. The volume-of-solid (VOS) method presented by Cheng and Chen [20] for homogeneous and isotopic materials shape design has been firstly applied to deal with the composite materials. The materials used to make the laminate largely determine the properties, costs, and thereby its suitability for different applications. In this study, three-layer laminated metallic composite materials are considered in the test problems. These metallic layers are made of copper, aluminum, stainless steel or iron. Two possible orientations of the composite materials, vertical and horizontal, are investigated. Optimal shapes of the thermal conduction path between a higher- and a lower-temperature isothermal surfaces are determined in order to maximize three different objective functions, namely $\dot{Q}/m$, $\dot{Q}/V$ and $\dot{Q}/USD$. By using the present approach, optimal thermal conduction paths leading to maximum heat transfer rate per unit mass, per unit volume, or per unit cost can be readily yielded.

1. Introduction

Topology optimization is a computational approach which optimizes material layout for given design space, material mass, loads or boundary conditions, such that the designed layout may meet the desired performance requirement. Using topology optimization, engineers can find the best conceptual design at a lower cost and in a shorter period of time. Recently, rapid growth in the rapid prototyping or 3D printing technology really helps advance the manufacturing of the complex shapes. With the help of 3D printing, engineers are able to present novel ideas of design that could not be manufactured before.

In the past several decades, the topological design concept is widely applied to structural optimization [1–3], mechanical design [4,5], and thermal problems [6–8]. The studies of structural optimization problems were focused on maximization of stiffness, shape or eigenfrequency [9,10]. As for the thermal optimization problems, it is typically to find an optimal shape of an object that leads to maximum heat transfer performance [6–8]. Nowadays, there have been a number of topology optimization methods proposed, such as solid isotropic material with penalization (SIMP) method [11], evolutionary structural optimization (ESO) method [12], and constructal method [13], and so on. In the field of heat conduction structures, the progress of the optimization methods has also been advanced recently. For example, Bejan and coworkers [14,15] developed a tree network for heat transfer based on the constructal theory. Guo, Cheng, and Xia [16] performed heat conduction structure optimization based on the least dissipation principle of heat transport potential capacity for several practical examples. Cheng and Chang [17,18] designed the shapes for cylinders and sliders to meet different required loading conditions by means of the simplified conjugate-gradient method (SCGM) proposed by the same group of authors [19]. Most recently, Cheng and Chen [20] presented a novel approach based on the solution of the volume-of-solid function equation (VOS equation) in a non-constrained formulation. The VOS method was successfully applied for topology design of heat conductive solid paths made of homogeneous materials.

The materials used to make the laminates largely determine the properties, costs, and thereby its suitability for different applications. For example, copper conducts heat evenly and quickly due to its high conductivity; however, cost of it is relatively high compared to other metals like stainless steel and iron. It might be

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Nomenclature

k_{eff}	effective thermal conductivity, W m^{-1} K^{-1}
k_s	thermal conductivity of pure solid, W m^{-1} K^{-1}
L	side length of original design domain, m
m	total mass of solid materials in use, kg
n	power constant in effective thermal conductivity equation
N	normal coordinate to boundary of original design domain
$\dot{Q}$	heat transfer rate, W
S	coefficient of Equation (3), W m^{-1}
T	temperature in original design domain, K
T_s	pure solid temperature in heat conduction path, K
V	total volume per unit length, m^2
x, y	rectangular coordinates, m
USD	total cost, in US dollar

Greek symbols

α	boundary of constant-temperature object
ζ	volume-of-solid function
ζ_c	optimal cut-off value of VOS function

Subscripts

i	index of constant-temperature object
j	index of layer

a benefit to have a mix of materials to form a multiple-layers structure to take advantage of the better properties of each material and avoid properties that may have a negative effect. The point is that there should be a balance between the function and the cost of the materials.

Thermal behavior of the laminated metallic materials is one of the interesting issues which has been widely investigated [21–25]. However, the previous studies of the laminated metallic materials were majorly focused on mechanical or thermal properties like effective thermal conductivity. To the authors' knowledge, there is no published article relevant to shape design or topology optimization for the laminated metallic materials. For the laminated metallic materials, an essential issue is how to design the structures with a rational distribution of the shapes of the metals layers so as to increase the heat transfer rate but reduce the mass or cost of metals utilized. However, the determination of the heat transfer path in the laminated metallic materials is a relatively complicated task because it involves different metallic layers. It definitely cannot be carried out merely based on the experience of the designers or by costly experiments.

Under these circumstances, in this study computation optimization of the laminated metallic materials is attempted. The concept of the VOS method proposed by Cheng and Chen [20] is firstly employed to optimize the conduction path in the laminated metallic materials between unequal isothermal objects. In this study, three-layer laminated metallic composite materials are considered in the test problems. These metallic layers are made of copper, aluminum, stainless steel or iron. Copper and aluminum are relatively high conductive metals for heat conduction; however, prices of them are high. On the other hand, conductivities of stainless steel and iron is relatively low compared to copper and aluminum, whereas their prices are also low. Densities and thermal conductivities [26] and prices of the selected metals [27] are provided in Table 1. Note that the prices of the metals were part of the

Table 1
Thermal conductivities and prices of selected metals.

Metal	Densities [26] [kg/m^3]	Thermal conductivity [26] [W/m K]	LME official price [27] [USD/kg]
Copper	8933	401	7.375
Aluminum	2702	237	1.815
Stainless steel (AISI 304)	7900	14.9	0.30
Iron	7870	80.2	–

statistics published by London Metal Exchange (LME) website on December 27, 2013 [27].

Two possible orientations of the metallic layers of the composite materials, vertical and horizontal, are taken into consideration. Table 2 shows the labeled cases with their orientations and metals used. Fig. 1 shows the schematic of the physical models. The design is carried out in a design domain having an area of 10 cm × 10 cm. Sizes of the hot and the cold objects are set to be 10/3 cm and 5 cm, and temperatures of the hot and the cold objects are maintained at 80 °C and 30 °C, respectively. In this study, the locations of the hot and the cold objects are fixed.

Conventionally, the optimization tasks were performed by building a mathematical model which minimizes an objective function subject to some certain constraints. A suitable thermal performance index must be selected as the objective function. In some certain existing studies, for example, Ref. [28], the constraint of the optimization of heat conduction structure is given with a fixed amount of mass m. Using this constraint, one may obtain some interesting results. However, firstly, this constraint can only fix the amount of solid mass in use rather than increase the utilization efficiency of the solid mass. In real engineering applications, fixing mass is not a practical constraint because a designer is not able to know the amount of mass before he starts designing. If the designer does not know the amount of mass, fixing mass is not meaningful. Secondly, because the metals used in the laminate have different densities and even prices. Thus, for the laminated materials composed of different metals it does not make any sense to design the structure simply by fixing the total mass m.

Therefore, in this study the optimal shapes of the conduction path in the laminated metallic materials between a higher- and a lower-temperature objects are determined based on three objective functions, $\dot{Q}/m$, $\dot{Q}/V$ and $\dot{Q}/USD$, where m, V and USD represent total mass, total volume and total cost, in US dollar, of the metals used in the laminate.

The topology optimization is actually non-constrained by directly maximizing the magnitudes of the individual objective functions, not just fixing m. Based on the present concept, optimal thermal conduction paths leading to maximum heat transfer rate per unit mass, per unit volume, or per unit cost can be pursued for improving the utilization efficiency of the solid materials.

Table 2
Labeled cases and their specifications.

Case	Orientation	Layer 1	Layer 2	Layer 3
Case V1	Vertical	Copper	Aluminum	Stainless steel
Case V2		Copper	Stainless steel	Aluminum
Case V3		Copper	Iron	Aluminum
Case H1	Horizontal	Copper	Aluminum	Stainless steel
Case H2		Copper	Stainless steel	Aluminum
Case H3		Copper	Iron	Aluminum