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Investment casting and experimental testing of heat sinks designed by topology optimization

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ABSTRACT

Topology optimization (TO) is an attractive numerical tool to obtain optimized engineering designs, which has been originally developed for mechanical optimization and extended to the area of conjugate heat transfer. With rapid developments in topology optimization models, promising designs have been proposed and presented recently for conjugate heat transfer problems. However, only a very small number of experimental validations of TO heat transfer devices have been reported. In this paper, investment casting (IC) using 3D stereolithography (SLA) printed patterns is proposed to fabricate 3D metal heat transfer devices designed by TO. Three heat sinks for natural convection are designed by a previously reported topology optimization model and five reference pin-fin heat sinks are devised for comparison. From those designs six heat sinks are cast in Britannia metal, fully reproducing the complex 3D optimized designs. It shows that SLA-assisted IC is a very promising technology with low cost and high accuracy for fabricating TO metal parts, which is not limited to heat transfer devices and can be extended to other areas such as structural optimization. A natural convection experimental setup is used to experimentally study the performance of the fabricated heat sinks. The results show that the tested TO heat sinks can always realize the best heat dissipation performance compared to pin-fin heat sinks, when operating under the conditions used for the optimization. Moreover, validation simulations have been conducted to investigate the temperature distribution, fluid flow pattern and local heat transfer coefficient for the TO and pin-fin designs, further evidencing that TO designs always perform better under the design conditions. In addition, the impact of heat sink orientation and radiation are presented.

1. Introduction

Topology optimization is a method that optimizes material distribution within a design domain for maximizing a desired objective function under given constraints. TO was originally developed for structural mechanics but has since been applied to different areas such as acoustics, fluid mechanics, conjugate heat transfer, and several others [1,2]. To set up the optimization, boundary conditions, constraints and an objective function are defined first and the finite element method is usually used to model the physical problem. The design is usually improved iteratively using a variety of algorithms like density based topology optimization, level set, topological derivative, phase field and evolutionary approaches [3].

During the last decade, several studies have been presented to optimize flow, conduction, convection and conjugate heat transfer problems, which were reviewed in Ref. [4]. Bruns [5] used topology optimization to study steady-state convection-dominated heat transfer problems. Yoon [6] presented a study of 2D thermofluid topology optimization of heat dissipating structures with forced convective heat transfer. Topology optimization of heat and mass transfer problems was investigated by Marck et al. [7] and the authors presented three examples of conjugate heat transfer, including a full bi-objective optimization. Coffin and Maute [8] showed 2D and 3D topology optimization of convective heat transfer problems, using the level set method. In their study, the convection coefficient was assumed constant, but an artificial diffusive model was introduced for the fluid temperature to avoid internal cavities. Topology optimization was applied to liquid jet impingement on a cold plate in order to maximize heat transfer over a plate while minimizing pump work [9] and a detailed experimental

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Nomenclature

Variables

A	area
A_m	convective heat transfer area
c_p	specific heat
g	gravity
h	convective heat transfer coefficient
I	current
k	thermal conductivity
p	pressure
Q	heat transfer power
$q'''(x)$	volumetric heat generation
T	temperature
T_m	metal surface temperature
T_0	ambient temperature
u	fluid velocity vector
V	voltage
x_{cond}	thermal conduction distance

Greek letters

α	orientation angle of the heat sink with respect to gravity (polar angle)
α_B	Brinkman penalization coefficient
β	coefficient of thermal expansion, rotation angle of the heat sink (azimuthal angle)
γ	density field for topology optimization (0 represents solid and 1 represents fluid)
ϵ	emissivity
μ	kinematic viscosity
ρ_0	density of the fluid
σ	Stefan-Boltzmann constant

Subscripts

a	air
Brit	Britannia metal
conv	convection
eff	effective
f	fluid
m	metal
rad	radiation
s	solid

evaluation of the heat sink design was presented by Dede and Liu [10]. The jet impingement design was then expanded to an array of jets fed by a topology optimized manifold that distributed equal fluid flow to each jet [11]. Koga et al. [12] used topology optimization to design a heat sink system for minimizing the pressure drop in the fluid flow and maximizing the heat dissipation effect. Dede [13] presented topology optimization of steady state convection-diffusion heat transfer problems using the commercial simulation software COMSOL Multiphysics [14]. An example of the channel topology was given for minimizing the mean temperature and total dissipated fluid power. Dede et al. [15] further fabricated a TO heat sink using metal additive manufacturing and experimentally compared its performance to convectional fin/pin-fin heat sinks. Haertel and Nellis [16] applied density-based topology optimization to heat exchanger design assuming a fully developed internal flow. The pressure drop and air-side temperature change were prescribed and the conductance of the heat exchanger was maximized. Alexandersen et al. [17] developed 2D topology optimization of heat sinks for natural convection using the steady-state incompressible Navier–Stokes equations coupled to the thermal convection–diffusion equation through the Boussinesq approximation. This work was further extended to 3D by using a large scale TO framework to design heat sinks with an order of 20–330 million state degrees of freedom in Ref. [18]. In addition, this TO tool was applied to design heat sinks for light-emitting diode lamps [19,38]. The optimized designs from Refs. [19,38] were produced using selective laser melting of an aluminum alloy and tested compared to a comparable pin fin heat exchanger [20]. Dilgen et al. [21] applied topology optimization to a forced convection heat sink for turbulent flow in 3D and showed that complex 3D designs can be obtained. This paper presents a continuing study based on Refs. [19,38] and using a similar approach as Ref. [20], in which we design passive heat sinks for natural convection. However, here we cast them using the lower cost lost wax method, and implement related experimental tests, including an additional comparison with simple pin fin designs.

As mentioned above, the experimental validation of TO conjugate heat transfer devices has rarely been carried out and only six related studies, Refs. [9–12,15,20], can to our knowledge be referenced, although a large number of topological designs of conjugate heat transfer problems have been presented. This is partly due to the fact that most presented topology optimization works treat rather academic problems with e.g. artificial material properties or unrealistic operating conditions, which cannot be easily converted to prototypes suitable for experiments. Another issue is that topology optimized heat transfer devices often exhibit complex shapes with fine features or complex geometries, which may be challenging or time consuming to manufacture using traditional machining methods. However, alternative manufacturing techniques such as stamping or casting could be promising for mass production of TO designs. New developing technologies such as metal additive manufacturing (AM), typically selective laser melting, thus become very attractive to fabricate 3D topology-optimized designs. A good example is the work presented by Dede et al. [15], showing that combining metal AM and TO designs is a promising path to develop new heat transfer devices. Lazarov et al. [20] also demonstrate that TO designs can outperform conventional designs for natural convection applications using AM metal heat exchangers. Although metal AM is becoming a mature technology and has been applied in specific areas including aeronautical and medical industries, there are still some limits to fabricate TO thermal devices using metal AM, such as high cost, limited material selection, potential reduction in thermal properties due to porosity in the structure and difficult post-processing. Therefore, this paper proposes investment casting assisted with stereolithography 3D printing, “SLA-assisted IC for short,” to fabricate metal devices designed by topology optimization as an alternative.

Investment casting is one of the oldest manufacturing processes, which is still widely used for fabricating jewelry and industrial metal products [22]. In the traditional IC process, the wax pattern is shaped into the desired pattern by hand or injection molding and is then surrounded with a refractory (the investment) that sets in the mold. By heating the mold, the wax pattern melts and flows out, forming a continuous cavity. Then molten metal at the proper casting temperature is poured into the mold. After cooling, the mold is broken and the solidified metal part is removed