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The utilization of selective laser melting technology on heat transfer devices for thermal energy conversion applications: A review

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ABSTRACT

This paper reviews advanced heat transfer devices utilizing advanced manufacturing technologies, including well-established thermal management applications. Several factors have recently contributed to developing novel heat transfer devices. One of the potential technologies revolutionizing the field of energy conversion is additive manufacturing (AM), colloquially known as three-dimensional (3D) printing. This technology permits engineers to develop a product with a high level of freeform features both internally and externally within a complex 3D geometry. Among different AM approaches, selective laser melting (SLM) is a well-used technique for developing products with a lower cost-to-complexity ratio and quicker time production compared to other manufacturing processes. The integration of SLM technology into heat exchangers (HXs) and heat sinks (HSs) has a strong potential, especially to fabricate customized and complex freeform shapes. The aim of this research is to review the advancement in design complexities of different industrial heat transfer devices incorporating metal SLM fabrication. The review is not meant to put a ceiling on the AM process, but to enable engineers to have an overview of the capabilities of SLM technology in the field of thermal management applications. This review presents the opportunities and challenges related to the application of SLM technology in connection to novel HXs and HSs, as well as heat pipes (HPs). The latter are passive heat transfer devices utilized in many thermal control applications, especially related to electronics cooling and energy applications.

1. Introduction

During the last decades, increasing heat transfer in many industrial applications has been a major concern, therefore researchers have been engaged to develop new energy saving and conversion strategies for different applications. The utilization of a heat exchanger (HX)/heat sink (HS), as a heat transfer device, is important for a variety of thermal control systems, energy storage systems and energy conversions applications include refrigeration cycles, heat recovery, automotive industry and electronic equipment, as well as renewable energy applications, including fuel cells, thermal energy storage and geothermal [1–5]. In addition, heat pipes (HPs), as passive heat transfer devices that operates by utilizing the latent heat of an internal working fluid, are also progressively used in industry [6–8]. A unique feature of HPs is that the evaporator and condenser sections can be separated by a large distance, and thereby experiencing a minimal temperature difference while transferring large amounts of heat. Hence, energy (heat) can be transported with very low thermal losses. Their simplicity as well as widely varying sizes, shapes and materials allow them to be used in different HX/HS applications [9–11].

Despite the impressive progress that has been made during the past decades on development of HXs/HSs, there are still serious technical challenges in thermal management of compact devices, mainly due to the growing power density, owing in part to increased performance requirements. For example, the maximum chip heat flux of high-performance electronic devices will increase up to 190 W/cm^2 [12] as illustrated in Fig. 1. This provides the requirement for the development of high performance HXs/HSs. For this aim, advances in the manufacturing methods that can precisely fabricate fully functional compact and efficient heat transfer devices is important in engineering applications. They should result in the use of less space and material, and allows for higher thermal loads and power densities. In light of this scenario, a significant effort has been carried out towards additive manufacturing (AM) approaches [13–24].

AM, formerly coined as rapid prototyping and rapid tooling, is also referred to as three-dimensional (3D) printing. Unlike conventional manufacturing processes, AM can directly produce complex 3D parts, with near net shape. It is a process whereby a 3D solid object is fabricated directly from the digital CAD file. AM products are built using successive layers of material that are stacked and bonded, in which

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Nomenclature

d_p	Powder particle diameter (m)
f	Friction factor
h	Heat transfer coefficient (W/m^2 K)
k	Thermal conductivity (W/ m K)
K	Permeability (m^2)
Nu	Nusselt number
r_p	Powder radius (m)
r_c	Capillary radius (m)
Re	Reynolds number
u	Velocity (m/s)

Greek symbols

ε	Porosity (dimension less)
ρ	Density ($kg\,m^{-3}$)
μ	Dynamic viscosity (Pa s)
σ	Surface tension ($N\,m^{-1}$)
θ	contact angle (°)

Subscripts

eff	Effective
l	Liquid
s	Solid

Abbreviations

AM	Additive manufacturing
CAD	Computer-aided design
HP	Heat pipe
HS	Heat sink
HX	Heat exchanger
LHP	Loop heat pipe
SLM	Selective laser melting
PHP	Pulsating heat pipe

each layer holds the shape of a slice of the digital model. AM techniques can be grouped based on the energy source (laser/electron beam), feedstock form (powder/wire) and feeding system (powder bed/blown powder) [25,26]. Each method has its own advantages and drawbacks depending on cost, materials, etc. Details on these manufacturing methods can be found in many reviews [27–32]. The most promising type of AM for fine industrial purposes is the approach using a laser beam as a source of energy and a powder bed system. This technology, selective laser melting (SLM) is the focus of the current review. Through SLM, a part is built by selectively melting material supplied in the form of a fine powder within a powder bed. This approach provides a method for fabricating a single complex geometry that could offer a range of advantages compared to conventional manufacturing techniques, including reducing the total number of parts, higher production rate, unique design and less geometrical constraints [33,34]. These features make SLM technology an important tool in terms of industrial applications [35,36], particularly in highly customized, freeform parts for the thermal management sectors [37–44].

The application of SLM technology within the thermal management field is facilitated by the ease of converting modern heat transfer devices into CAD designs. One ability of SLM is optimizing heat transfer through HX/HS systems to increase surface area of the same length size in comparison of traditional manufactured systems. For an example, traditional HSs employ surface area extensions such as pins and fins for increasing the surface area [45]. This effect can be drastically enhanced by employing an SLM approach [37,38]. In addition, geometrical features on the part could be manufactured to enhance flow mixing, resulting in a further enhancement in heat removal [46]. Another advantage of SLM technology are integrated composite structures or multi-material fabrication [47] to optimize parts of a product, including high thermal conductivity, ease of integration with the heat dissipation component, etc. Therefore, the potential of utilizing SLM in the production of functional heat transfer components such as HXs, HSs and HPs has recently received increased attention.

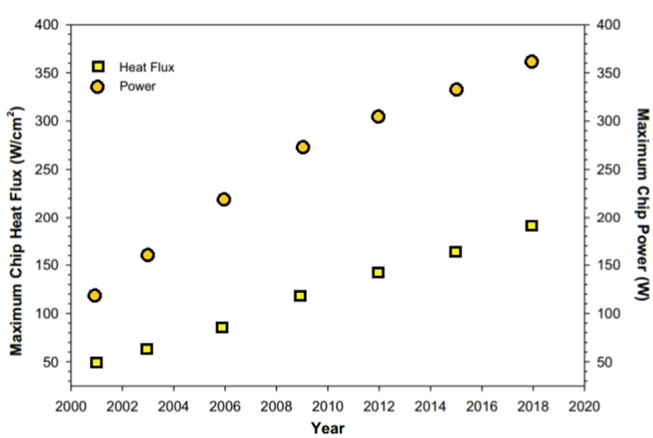

Fig. 1. Power trend high power electronic applications [12].

The study of the fluid flow through porous media structures has also become a popular research subjects in many engineering fields [48–50] and partially also in HXs/HSs and HP research in the thermal management field [51–54]. The fabrication of porous structures has been extensively explored by traditional methods including liquid state processing, solid state processing, electro-deposition and vapor deposition [55]. However, only limited control over the internal structure can be achieved by conventional processes to achieve stable production. Although the shape and size of the pores can be adjusted by changing the parameters of these manufacturing processes, only a randomly organized porous structure can be achieved [56]. Porous structures have been developed recently due to the advancements in AM. SLM technology can fabricate porous structures with predefined net-shape fabrication as well as a range of material choices and shorter process cycle. Hence, enabling the fabrication of highly complex porous structures [57–59]. Furthermore, AM offers the promise of freeform HPs, optimizing heat transfer in given operational conditions. Unique is that the wall and wick are built up together, thereby minimizing thermal resistance. Further integration could even lead to a HP in combination with an external HS to have ideal external thermal contact as well.

All-in-all, SLM is an emerging fabrication technique that shows great advantages and potential compared to conventional methods [28,60]. The challenges of SLM manufacturing include a variety of parameters (powder characteristics and procedure) as well as process parameters (laser power, laser speed and layer thickness) [25,26,34,61]. Also, the design of SLM-fabricated parts is significantly different compared to parts that are fabricated conventionally. Despite the advantages of SLM technology, there has been only limited work in its implementation for HXs/HSs fabrication and associated porous media structures. Several reviews of AM printing techniques are available addressing utilizing of this advance manufacturing in different applications [15,16,19–21]. However, there is no compilation of literature or state-of-the-art review in the enhanced metallic surface technology and porous structures for heat transfer improvement as well HP technology and HXs/HSs utilizing laser AM.