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Thermal Characteristics of Additively-Manufactured Metamaterial Structures in Air flow Condition

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The metamaterial structures exhibit various mechanical properties such as high strength/stiffness, energy absorption, and lightweight. Additionally, it has unprecedented thermal performances via high specific surface area and complex flow patterns inside the pore. Accordingly, the metamaterial structures have been widely studied in recent years because of these advantages, having a great attention as the thermal management structures for transportation, manufacturing, and electronics industries. In this study, thermal performances and fluid flow characteristics of the metamaterial structures were comprehensively explored for them to be used in a 3D cooling channel system in a mold. The performances of metamaterial structure channels, fabricated with the powder bed fusion (PBF) technique and using 17-4 PH stainless steel, were numerically and experimentally investigated. It was observed that, in case of forced convection, complex flow pattern and porosity ratio of the structures affected the heat dissipating ability and pressure drop, which is encouraged to be improved via a porosity graded design. It was confirmed that the shape, wall thickness and specific surface area of the structures determines heat dissipation in the forced convection. The investigated characteristics can be applied to the design of 3D cooling channel mold.

This work could give an understanding of the correlation between air convection and thermal characteristics of various metamaterial structures along with the mechanical properties of them. Moreover, the structures could be a guideline for designing the structures for the industrial applications such as thermal insulation, heat dissipation and cooling channel system.

NOMENCLATURE

A = surface area (m^2)
D_h = hydraulic diameter (m)
f = friction factor
L = length of the channel (m)
$\bar{h}$ = overall convective heat transfer coefficient (W/m^2·K)
ΔP = pressure drop (kPa)
Q = heat rate (W)
Re = reynolds number
$T_{aver.}$ = average temperature (℃)

Greek Symbols

ρ = density (kg/m^3)
ε = porosity ratio (%)
μ = dynamic viscosity (kg/m·s)
σ_{st} = standard deviation temperature (℃)

1. Introduction

Metal additive manufacturing (AM) provides greater design freedom than traditional manufacturing techniques such as milling, drilling and casting because it enables the fabrication of complex geometric structures. Advances in additive manufacturing technology have enabled to manufacture metamaterial structures with mechanical properties that do not exist in nature. In particular, the metamaterial can provide geometric advantages such as a high surface area to volume ratio required for convective heat transfer, and can improve heat transfer performance by creating complex flow patterns. Therefore, these key characteristics have shown high potential for convective cooling structures such as heat exchangers [1-4].

This study explores the potential of using internal structures of cooling channels in injection and casting molds requiring thermal management. The use of air as a cooling medium in the traditional hollow channel has been limited due to its characteristics of low heat capacity despite its eco-friednly and economical advantages. However, channels made of a metamaterial structure can greatly improve air cooling performance.

So in this study, the heat transfer performance of metamaterial channels in air flow condition was investigated to confirm the feasibility of using air as a coolant. This study aslo investigates the air forced convection of the lattice and the TPMS (Triply Periodic Minimal Surface) structures, and along with the effect of functionally graded porous structures.

2. Materials and Methods

2.1 Design and fabrication

As depicted in Fig. 1, lattice-based FBCCz and Octet-truss unit cells and TPMS-based Gyroid and Diamond sheet unit cells were chosen for the inside structure of the cooling channel. 8mm unit cells are periodically arranged inside the channel, and the wall thickness of the unit cells for comparison is designed having the same porosity ratio. To fabricate channels, metal AM process was used and 17-4 PH stainless steel was prepared from AMC powder company. The optimum processing parameters are as follows: laser power, scan speed, hatch space and layer thickness were 250 W, 600 mm/s, 135 µm and 40 µm respectively.

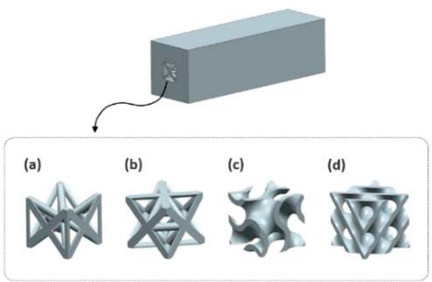

Fig. 1. Unit cells of cooling channel (a) FBCCz. (b) Octet-truss. (c) Gyroid sheet. (d) Diamond sheet.

2.2 Experimental setup and procedures

The experimental setup was depicted in Fig. 2. The metamaterial channel was heated with a constant heat flux on one side by an aluminum block with a cartridge heater inserted therein. Compressed air was supplied to the channel at constant pressure and flow rate using a regulating valve. Insulated steel pipe with a diameter of 8 mm and a length of 300 mm was set before and after the channel, and the air passing through the channel was emitted to the atmosphere. The air flow rate was measured using a thermal flowmeter, and T-type thermocouples and pressure sensors were set before and after the channel to measure temperature and pressure drop. The same thermocouples were embedded inside the walls of the channels as well, and all sensors were connected to data acquisition equipment.

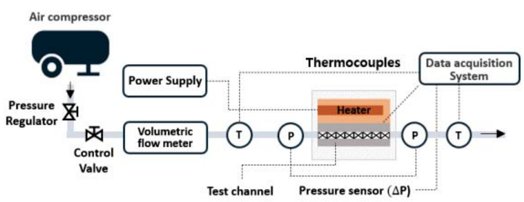

Fig. 2 Schematic of experimental set-up for metamaterial channels.

2.3 Numerical simulation

In order to investigate the mechanism and thermal characteristics of air convection inside the channel, steady-state numerical simulation was conducted using Ansys fluent, a commercial CFD software. Fig. 3 shows a computational domain and boundary conditions for the simulation. And also detailed conditions about the CFD simulation can be found in Table. 1. For a robust and accurate simulation of near wall treatment, the height of the first layer elements was generated small enough to guarantee a dimensionless wall distance (y+) of less than 1.

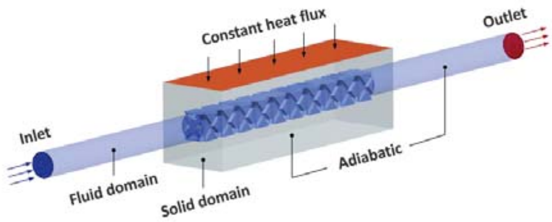

Fig. 3 Schematic of the CFD domain and boundary conditions

Table. 1 CFD set-up conditions.

Physics	Model
Time	Steady-state
Tubulent	Shear stress transport (SST) k-ω
Fluid domain	Ideal air
Solid domain	17-4PH
Wall	No-slip condition
Mesh	Hybrid mesh (tetrahedron and prism elements)

The Reynolds number (Re) is defined based on the following equation:

$$Re = \frac{\rho U_f D_h}{\mu}$$

The overall convective heat transfer coefficient ($\bar{h}$) is defined as Newton's law of cooling.

$$\bar{h} = \frac{Q}{A(T_{wall} - T_{fluid})}$$

The non-dimension pressure loss in the channel was expressed as the panning friction coefficient (f):

$$f = \frac{\Delta P D_h}{2L\rho {U_f}^2}$$

2.4 Model validation

The forced convective heat transfer performance and pressure drop predicted by the simulation model were compared with the experimental results. Fig. 4 shows the heat transfer coefficient and pressure drop of the 17-4PH hollow channel fabricated by machining and the FBCCz lattice channel. It was seen that the experimental and simulated values agree well within the maximum deviation of 10%. The main cause of the deviation can be explained by the roughness inside the channel formed during the AM. Therefore, the simulation model was validated to investigate the air convection mechanism inside cooling channels.

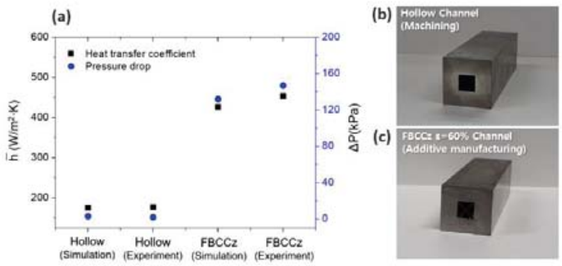

Fig. 4 Validation of (a) predicted heat transfer coefficient and pressure drop at Re = 32,500 and heat rate = 30 W (Hollow vs FBCCz ε = 60%).
(b) Hollow channel. (c) FBCCz channel.

4. Conclusions

In the lattice structure-based FBCCz and Octet-turss channels, it was confirmed that straight flow is dominant. On the other hand, in the TPMS structure-based gyroid and diamond sheet channels, helical flow characteristics could be observed due to the geometric porous shape (Fig. 5). And the vortex flows observed in all channels enhanced the convective heat transfer at the thermal boundary layer [5]. The high specific surface area and generation of turbulent kinetic energy of TPMS-based channels enabled excellent convective heat transfer performance, but higher pressure loss occurred as a trade-off effect due to high flow velocity and flow resistance characteristics (Fig. 6). Finally, the low density and specific heat characteristics of air could cause non-uniform heat transfer by increasing the air temperature in the flow direction. This phenomenon could be improved via functionally graded porosity structure [6] (Fig. 7). When designing functionally graded porosity structure, it is necessary to consider manufactrable wall thickness in the high porosity ratio part and excessive pressure difference in the low porosity ratio part.

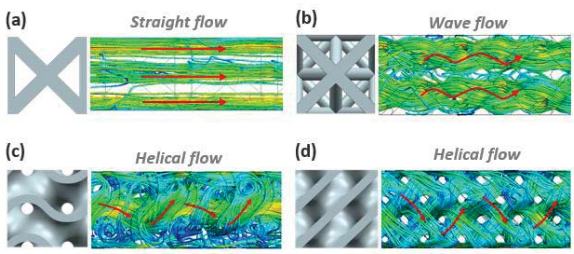

Fig. 5 Comparison of streamlines at Re = 32,500 and heat rate = 70 W (a) FBCCz. (b) Octet-truss. (c) Gyroid sheet. (d) Diamond sheet.

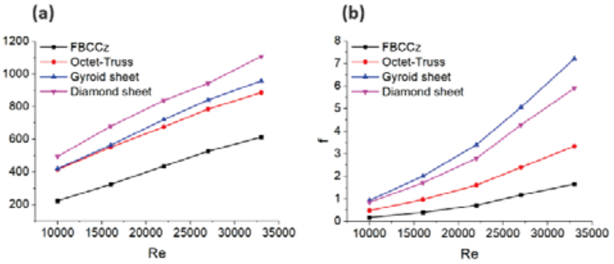

Fig. 6 Simulation results of (a) the overall heat transfer coefficient. (b) friction factor at different Re. and heat flux = 70 W.

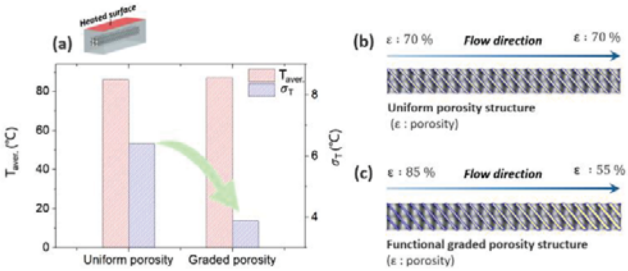

Fig. 7 Simulation results of (a) the heated surface temperature at Re = 32,500 and heat rate = 70 W (Diamond ε = 70% vs Diamond ε = 85~55% , Based on the same volume fraction). (b) Uniform porosity structure. (c) Functional graded porosity structure.

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