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HIGH-EFFICIENCY COOLING SYSTEM USING ADDITIVE MANUFACTURING

In this study, we propose a cooling structure manufactured using a specialized three-dimensional (3D) printing design method. A cooling performance test system with complex geometry that used a thermoelectric module was manufactured using metal 3D printing. A test model was constructed by applying additive manufacturing simulation and computational fluid analysis techniques, and the correlation between each element and cooling efficiency was examined. In this study, the evaluation was conducted using a thermoelectric module base cooling efficiency measurement system. The contents were compared and analyzed by predicting the manufacturing possibility and cooling efficiency, through additive manufacturing simulation and computational fluid analysis techniques, respectively.

Keywords: Additive manufacturing, DfAM (Design for Additive Manufacturing), Cooling system, Lattice structure, Simulation

1. Introduction

The use of additive manufacturing in the field of component design has enabled the direct design and manufacture of products with difficult shapes [1-3]. As the degree of integration of processing components improves, the space for discharging heat is gradually limited, furthering interest in high-efficiency compact heat exchange systems. In particular, it is expected that research areas, such as the use of microchannels, will develop according to the purpose and method of use of these systems [4]. When current passes through a thermoelectric module, a potential difference is generated, resulting in a temperature difference in the device owing to the Peltier effect. If the device is not effectively cooled, a thermal reversal phenomenon occurs and the cooling or heating effect cannot be maintained. To solve this problem, a heat exchanger is required. In conventional commercial products, as cooling fans are typically attached to a metal plate, installing a fan in the heating and cooling parts or for forced convection results in an increase in the thickness of the device. In recent thermoelectric cooling modules, they are applied to smart devices to maintain their fast response, and it is necessary to minimize the thickness and shape freely [5].

In this study, a design for additive manufacturing (DfAM) involving a lattice structure design is proposed to improve the heat transfer. DfAM is a general design method required for production using additive manufacturing and refers to the process of providing a function or a comprehensive understanding of the manufacturing feasibility, reliability, and costs of a product. The lattice structure method, which involves the manufacture of a product through a cell-type structure, has not been applied thus far owing to difficulties in the manufacturing process using conventional methods. However, in the additive manufacturing method, weight reduction and fast manufacturing speed can be obtained through the lattice structure, such that a lattice structure for a particular portion not subjected to stress is applied. According to a recent report, when various lattice structures are fabricated using a metal 3D printer, the change in material properties according to the relative density is systematically organized [6,7].

The application of metal 3D printing and computational analysis technology can provide an optimum design by bringing attention to problems expected during manufacturing and operation in the design stage of a product. In this study, we systematically examined a system construction method and computational analysis that can efficiently cool down in connection with a thermoelectric module using metal 3D printing. To design the additive manufacturing parts, a lattice structure was formed based on a specific shape created using a dedicated program in computer-aided design (CAD), and a model group

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was selected to systematically examine the relationship between flow and cooling efficiency according to the thickness of the lattice structure of each part. The model experiment indicated that the larger the volume occupied by the grid, the more heat exchange; and the flow decrease phenomenon was confirmed through computational fluid dynamics (CFD) analysis. The design of the lattice structure is important to design for optimal cooling efficiency. Because of limitations on materials and systems, calculations and experiments were conducted to build cooling systems using simple thermoelectric elements; however, the lattice structure can be applied to various shapes, unlike the existing fin shape. Through additive manufacturing analysis, it is possible to establish basic technology for virtual engineering manufacturing methods for the verify manufacturability and predict physical properties [8].

2. Experimental procedure

In the metal 3D printing process, various defects occur during manufacturing. Common defects include cracks and even breakage of products owing to the accumulation of thermal stresses during additive manufacturing. Some of these defects, such as collapse due to poor supporter, are difficult to predict at the time of design, and as they depend on the process conditions, a better understanding of the process is essential. To address this issue, additive manufacturing simulation technology has been proposed based on computational materials engineering, fluid analysis, and finite element stress analysis, although its use is still limited in several materials owing to the lack of experimental data. In this study, additive manufacturing simulations were performed on SUS 316L on which a relatively large amount of data is available. The amount of time deformation that can occur during the manufacture of a heat exchanger product with an X-shaped lattice structure was examined. The software used for this simulation was Autodesk's Local Simulation, which uses a mesh comprising a rectangular parallelepiped structure to effectively simulate a complex product. Information on the process conditions can enable fast calculations by the pre-calculation of necessary information using the layer thickness, scan speed, and laser power as variables and applying them to the mesh [9].

In this study, a system was constructed to investigate the cooling performance of a heat exchanger according to the internal lattice structure its parts made with a metal 3D printer. To test the cooling performance, a box of dimensions 26 × 26 × 24 cm was used to create a shielded environment. Inside the box, two heatsinks manufactured by a 3D printer were stacked, and a cooling fan (40 mm × 40 mm) was attached to the inlet for air. The entire system was assembled such that the cold side of the thermoelectric module was attached to one side of the heatsink and the hot side was in contact with the opposite side (Fig. 1). The cooling of the hot side of the thermoelectric module is particularly important. As the purpose of this experiment was to determine the cooling performance based on the internal lattice size of the heatsink made using a 3D printer, a commercial CPU cooler was used on the hot side of the thermoelectric module. The thermoelectric module used in this experiment was TEC1-12705, and the temperature was measured using an LCD digital thermometer. A power supply capable of operating at a maximum voltage of 30 V and a maximum current of 5 A was used to power the thermoelectric module and cooling fan, and 12 V power was supplied in the actual experiment.

In the overall system, a structure for cooling was arranged in the high-temperature part within the center of the thermoelectric module, and the cold air obtained by the thermoelectric effect was ventilated to improve the flow of air in the low-temperature part. The basic frame structure was the same, and the internal lattice was created using the Autodesk Netfabb Ultimate version, a DfAM-dedicated software. The shape of the lattice can be selected as required. Because heat conduction and mechanical properties differ depending on the lattice structure, systematic research is required. In this study, because the basic (+)-type lattice structure requires supporter owing to the high overhang angle, the X-type lattice structure, which is most actively used in the additive manufacturing process, was applied and the size of the single grating was fixed at 4 mm. To examine the change in heat transfer with varying thickness of the lattice, thicknesses of 0.5 mm, 1.0 mm, and 1.5 mm were selected, as shown in Fig. 2.

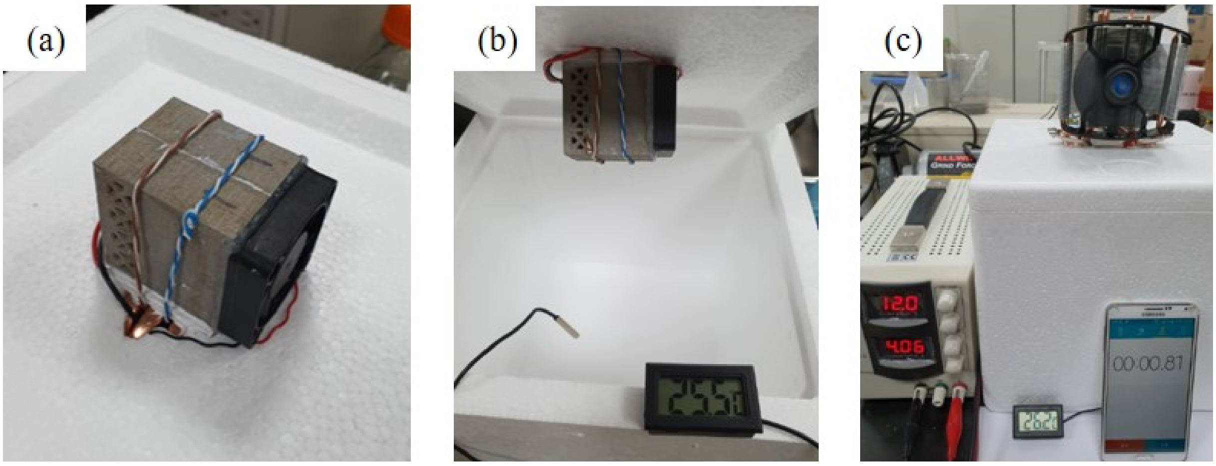

Fig. 1. (a) Heatsink parts with cooling fan; (b) Digital thermometer; (c) Overall system

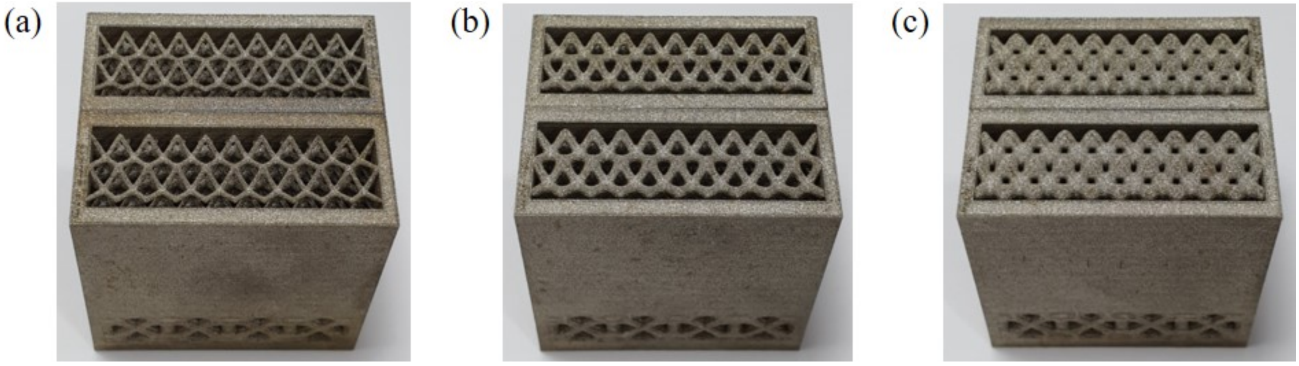

Fig. 2. (a) Heatsink 1. (b) Heatsink 2. (c) Heatsink 3. Heat exchanger parts manufactured in three different internal lattice sizes

If the lattice is excessively thin, the cooling gas may pass through without heat exchange, and if the flow path is narrow, the flow of the cooled gas is slow and cooling efficiency may be poor. The cooling efficiency according to the lattice thickness of the cooling channel is shown in Fig. 3.

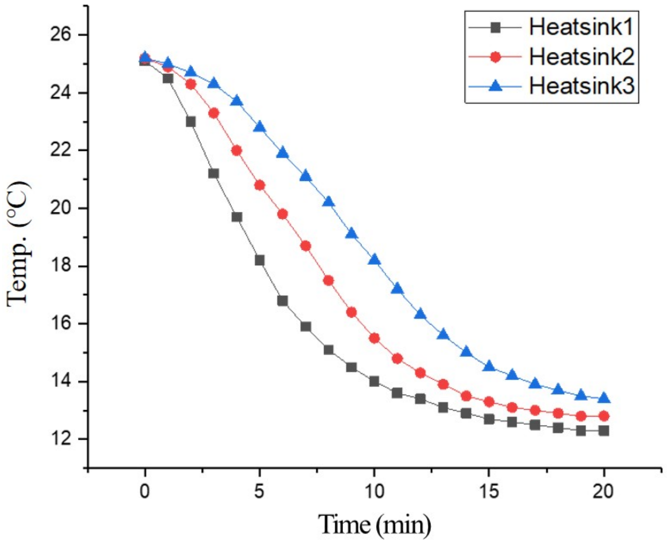

Fig. 3. Comparison of cooling efficiency for channels with internal lattices of different thicknesses. The temperature was measured every minute to analyze the cooling performance. There was a temperature change from approximately 25.1℃ to 13.6℃ over 20 min (the thicknesses of the internal lattice of heatsinks 1, 2, and 3 were 0.5 mm, 1.0 mm, and 1.5 mm, respectively).

Netfabb local simulation was used as the appropriate manufacturing simulation. This method fixes the conditions of the additive manufacturing method and performs calculations based on the analysis method to examine possible problems. The software simultaneously considers the applied powder layer and the amount of deformation and presents them as standard indicators. If stress is highly concentrated, it is reported that cracks may occur during cooling after completion of molding or during manufacturing, which should be considered in the design. In addition, three types of heat exchange systems were selected, and a model experiment was conducted to reveal the correlation between the cooling efficiency and lattice structure [10].

3. Results and discussion

SUS 316L, which exhibits excellent corrosion resistance and high strength, was selected as a material to build a cooling system through additive manufacturing with a lightweight design. Product manufacturing using high thermal conductivity and lightweight Al alloys is expected to proceed after reviewing design technology through simulations. Among the process parameters, high energy power and low scan speed enable the fabrication of dense and hard parts, and an excessive energy input reduces density because of the pinhole effect. The process conditions were set to a laser power of 350 W and a scan speed of 2800 mm/s to secure parts with high relative density based on previously reported analyses of mechanical properties.

The cooling performance test was conducted by measuring the temperature of three heat exchangers with different internal lattice sizes. In early experiments, it was found that although the designed lattice structure was 0.5 mm, it was possible to increase the cooling efficiency by transferring heat and reducing fluid flow. Computational fluid analysis is required to predict and utilize this information, and cooperative research has been conducted for this purpose. There was a temperature change from approximately 25.1°C to 13.6°C over 20 min. Over 5 min, the temperature change was 18°C for cooling channel 1 and 24°C for channel 3; which is a difference of 6°C. The larger the thickness of the internal lattice, the slower the fluid movement, and the longer it takes for the temperature to decrease. As the size of the lattice increases, the area in contact with the cold metal increases, and heat is effectively transferred; however, the overall cooling efficiency decreases owing to the decrease in flow (Fig. 3). Fig. 4 shows the thermal stress distribution and strain prediction results generated during the additive manufacturing of a heat exchanger with a 1.0 mm grid size. The figure shows the displacement that occurs as the additive manufacturing process progresses, and the large stress acting on the edge between the build plate and the product. Angular shapes can cause common problems in additive manufacturing, which can be reduced by changing the design to a curved surface. The original design was not modified in this study. The maximum stress level of the manufactured cooling system was 425 MPa, which was lower than that of the SUS 316L stress level (Fig. 4).

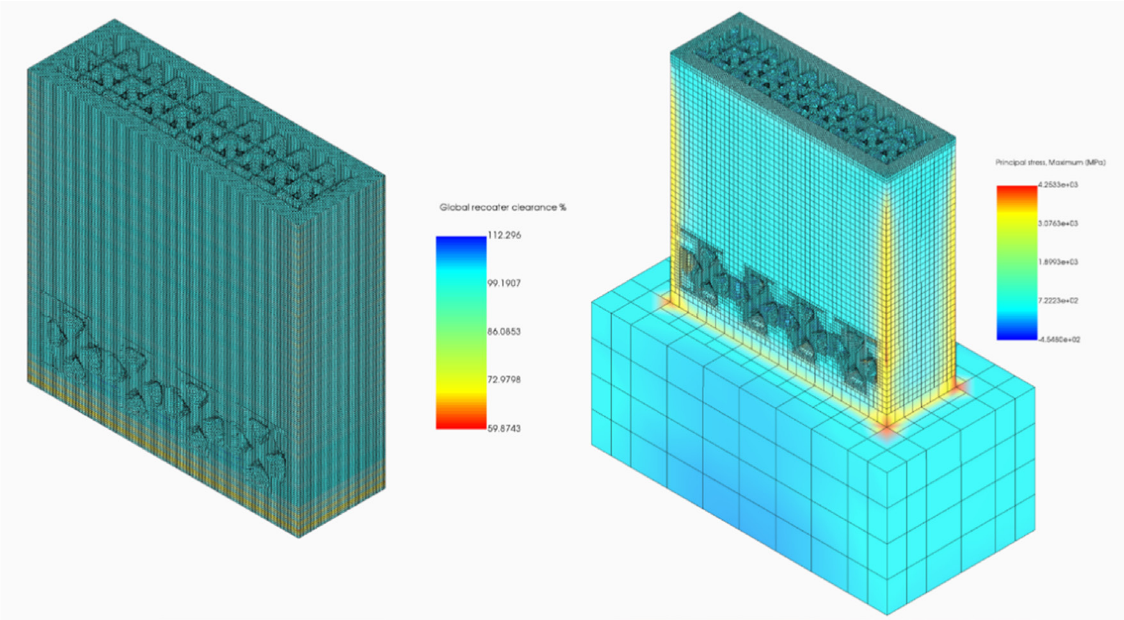

Fig. 4. Results of prediction of stress distribution and deformation occurring in additive manufacturing of a cooling system with a lattice structure (*t* = 1.0 mm). The stress largely acts at the corner between the build plate and the product. As the size of the cooling system to be manufactured is relatively small (44 × 8 mm), the maximum stress level is 425 MPa, which is less than the maximum stress of SUS 316L

Fluid and thermal analyses were performed using ESI's CFD-ACE for convenience. In the case of thermal analysis including fluids, it is important to set boundary conditions. Thus, the flow rate of the given system was set as the general condition for the calculation. To express the fan effect of the inlet, a pressure 100 Pa higher than the atmospheric pressure was applied under isobaric conditions, the surface temperature was fixed at 10°C, and calculations were performed. The outlet temperature was measured as the average temperature at a distance of 1 cm from the outlet, and the flow rate of the corresponding portion was calculated as the average value. Without a lattice structure, the flow rate was 418 cm^3/s and the outlet temperature changed by 0.8°C. However, in the case of a lattice structure, the flow rate decreased, and the change in the outlet temperature through heat transfer increased. When the grid thickness was 0.5 mm, the flow rate was 352 cm^3/s and the temperature change was 2.8°C; when the thickness increased (*t* = 1.0 mm), the flow rate decreased to 237 cm^3/s and the temperature change increased to 3.6°C. The flow and temperature changed according to the simulation results. At the initial inlet, the flow proceeded with the same pressure, but on the outlet side, the flow decreased with direction change and the temperature change linearly decreased as it passed through the exchanger (Fig. 5), which is common in typical heat exchangers. As the surface area increased, the outlet

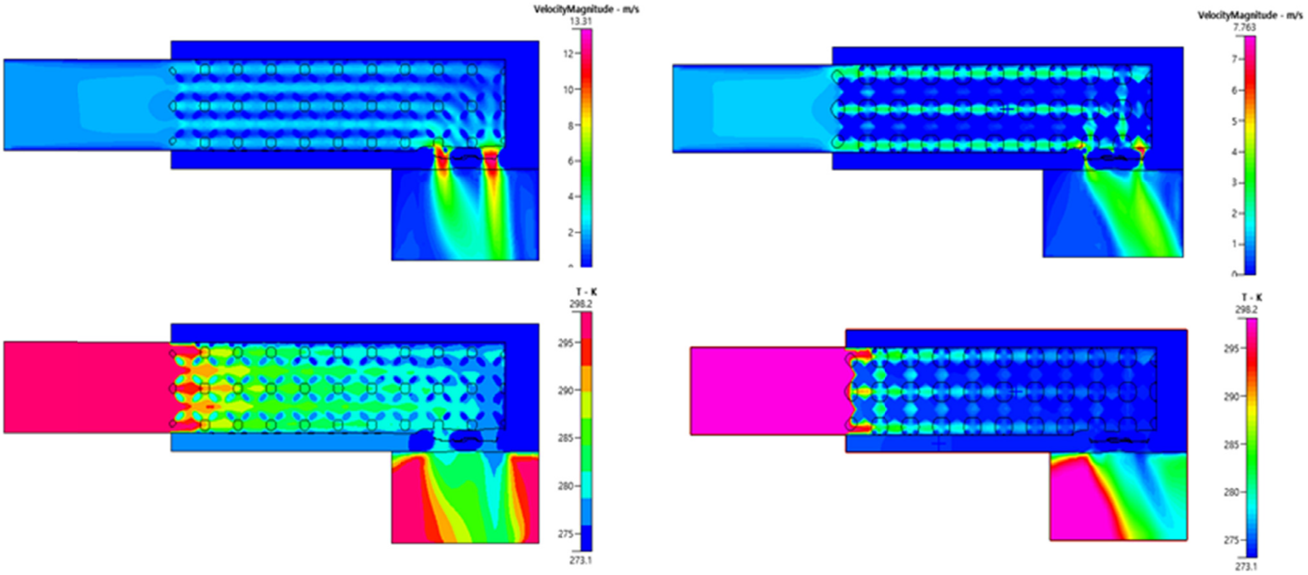

Fig. 5. Simulation results for flow rate and temperature change according to lattice thickness (left lattice thickness 0.5 mm, right lattice thickness 1.0 mm)

temperature changed, and as the flow path decreased, the flow rate decreased. Optimization requires additional calculations, but as described above, the flow rate and the degree of heat exchange depend on the grating thickness, and optimization of the design is required to account for the total energy transferred outside the entire system.

4. Conclusions

In this study, heat exchangers with different internal lattice sizes were manufactured using 3D printing and the difference in actual cooling was examined through experiments. The aim was to develop a compact cooling system through the integrated technology of metal 3D printing and thermoelectric modules, and the performance was tested by building a simple system. A lattice-structure-based cooling channel system was developed using the design of the additive manufacturing process, and manufacturing problems were reviewed through additive manufacturing simulations. A preliminary analysis of the cooling system was performed through simulation analysis, which allows future errors could be reduced. A measurement system was established for the flow and heat transfer problems based on the thickness of the lattice. In addition, results could be predicted using computational fluid analysis, which can be used in future databases. This study demonstrated the various possible applications of the grafting of metal 3D printing and next-generation energy devices. Systematic research on this topic is expected to help build an eco-friendly Internet of Things system.

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