International Core Journal of Engineering Volume 10 Issue 3, 2024
ISSN: 2414-1895 DOI: 10.6919/ICJE.202403_10(3).0015

Study on Heat Transfer Performance of Porous Structure for Heat Dissipation System

Jiahui Cao*

University of Shanghai for Science and Technology, Shanghai 200082, China

*caojiahui0926@163.com

Abstract

In recent years, porous materials have attracted attention for their excellent specific stiffness and strength, as well as their high heat dissipation capacity and multifunctional properties, and are being used in a wide range of applications such as medical devices, aerospace, and vehicles. As a porous structure with good internal pore connectivity and a large surface area-to-volume ratio, triply periodic minimal surface structures (TPMS) have the potential to be an excellent heat sink. In this paper, the thermal performance of four common TPMS structures, Gyriod, Diamond, Primitive and I-WP, are investigated to find out the porous structures with excellent thermal performance.

Keywords

TPMS; Thermal Conductivity; Finite Element Analysis.

1. Introduction

The TPMS architectures consist of continuous and interconnected networks, and a large number of similar geometries are readily found in nature, such as surfaces of surfactant-water systems, cell membranes, sea urchin plates, and block copolymers. Compared to strut structures, TPMS structures have a smooth and continuous geometry, which is less prone to stress concentration and higher structural strength. In addition, these metamaterials are very promising in the biomedical and heat exchanger fields due to their smooth surfaces [1-3].

At present, researchers at home and abroad have conducted a large number of studies on the thermal conductivity of TPMS structures through theoretical analysis, analog simulation, and experimental studies. Catchpole-Smith et al. built a test setup that can measure the apparent thermal conductivity of porous materials according to the ASTM E1225-13 test standard, and subsequently measured the apparent thermal conductivity of Primitive, Gyroid, and Diamond structures with different volume fractions and structural unit sizes prepared by SLM, respectively [4]. The experimental results show that for the same volume fraction, when convective heat transfer is not considered, the thickening of the wall thickness improves the efficiency of heat transfer, resulting in an increase in the apparent thermal conductivity of the structure, which is manifested by the fact that when the dimensions of the structural units are the same, the apparent thermal conductivity of the Primitive structure is larger than that of the other two structures [5]. Vignoles et al. calculated the effective thermal conductivity of a variety of TPMS structures using a hybrid random walk numerical method. The results show that the relative effective thermal conductivity (the ratio of the effective thermal conductivity of the porous material to the thermal conductivity of the matrix material) of the TPMS structures is about 0.61 times their volume fraction [6].

In this paper, the thermal performance of four common TPMS structures, Gyriod, Diamond, Primitive and I-WP, are investigated to find out the porous structures with excellent thermal performance.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202403_10(3).0015

2. Experiment

2.1 Design of the TPMS Structure

The Currently, the simplest and most commonly used method for designing TPMS lattices is the level set approximation. Level-set equations are a set of trigonometric functions that combinedly satisfies the equality $\emptyset(x, y, z) = c$. The four TPMS structures are generated and studied by the following mathematical equations:

TPMS-P $$\Phi p^*(r) = \cos(2\pi x) + \cos(2\pi y) + \cos(2\pi z) = c. \quad (1)$$

TPMS-I $$\Phi i^*(r) = 2[\cos(2\pi x)\cos(2\pi y) + \cos(2\pi y)\cos(2\pi z) + \cos(2\pi z)\cos(2\pi x)] - [\cos(4\pi x) + \cos(4\pi y) + \cos(4\pi z)] = c. \quad (2)$$

TPMS-G $$\Phi g^*(r) = \sin(2\pi x)\cos(2\pi y) + \sin(2\pi y)\cos(2\pi y) + \sin(2\pi z)\cos(2\pi x) = c. \quad (3)$$

TPMS-D $$\Phi d^*(r) = \cos(2\pi x)\cos(2\pi y)\cos(2\pi z) - \sin(2\pi x)\sin(2\pi y)\sin(2\pi z) = c. \quad (4)$$

The shape of a level-set surface is determined by the level-set constant c. Increasing or decreasing the level-set constant shifts the level-set surface in the direction of the normal, or in the opposite direction of the normal, and plots two or more surfaces corresponding to different values of the level-set constant together; these surfaces do not intersect. The above level set approximation equations can be used to easily map the TPMS, and based on these surface equations, solid structures can be generated mainly by increasing or decreasing the level set constants. As shown in Figure 1, all models are compiled and generated by MSLattice software. The CAD models shown in Figure 2 are the four TPMS structures with a relative density of 30%, respectively. In addition, the cell size was set to 3.33 × 3.33 × 3.33 mm, and each specimen consisted of 3 × 3 × 3 cells.

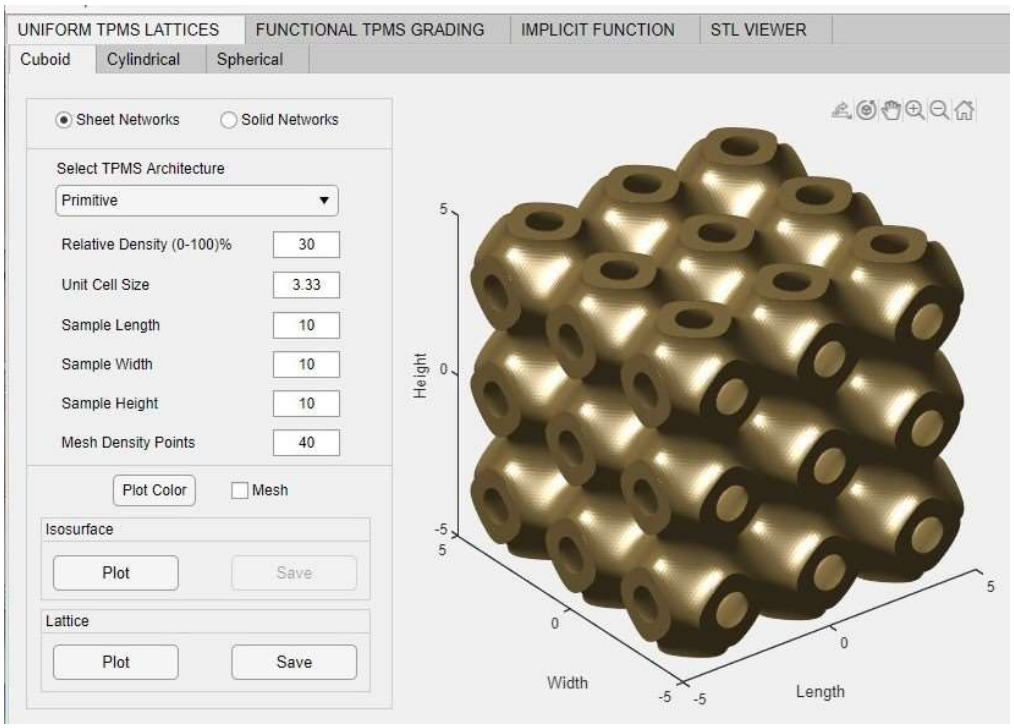

Figure 1. Design process of the TPMS structure

ISSN: 2414-1895 DOI: 10.6919/ICJE.202403_10(3).0015

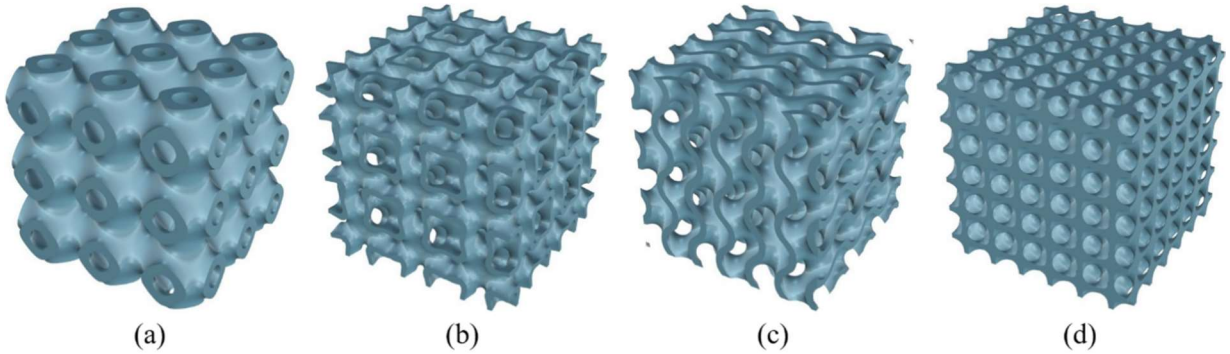

Figure 2. The four TPMS structures (a) Primitive; (b) I-WP; (c) Gyroid; (d) Diamond.

2.2 Finite Element Analysis of Heat Dissipation

The thermal conductivity process of porous materials is very complex, if the finite element model is not properly simplified, the model solution calculation process will consume a lot of time, and even lead to the results are not easy to converge. In this study, the radiative and convective heat transfer processes are ignored, and only the heat conduction process of the porous material is considered. Based on the energy conservation equation, the governing equation of heat transfer can be defined as:

$$\rho C_p \nabla T + \nabla(-\lambda \nabla T) = Q \tag{5}$$

In this study, titanium alloy TC4 was chosen as the matrix material for the solid phase in the simulation. Its boundary conditions in vacuum are shown in Figure 3: In this paper, only the heat conduction problem is considered, and a constant temperature load is applied to the upper and lower surfaces of the model, respectively, and the rest of the surfaces are set to be thermally insulated.

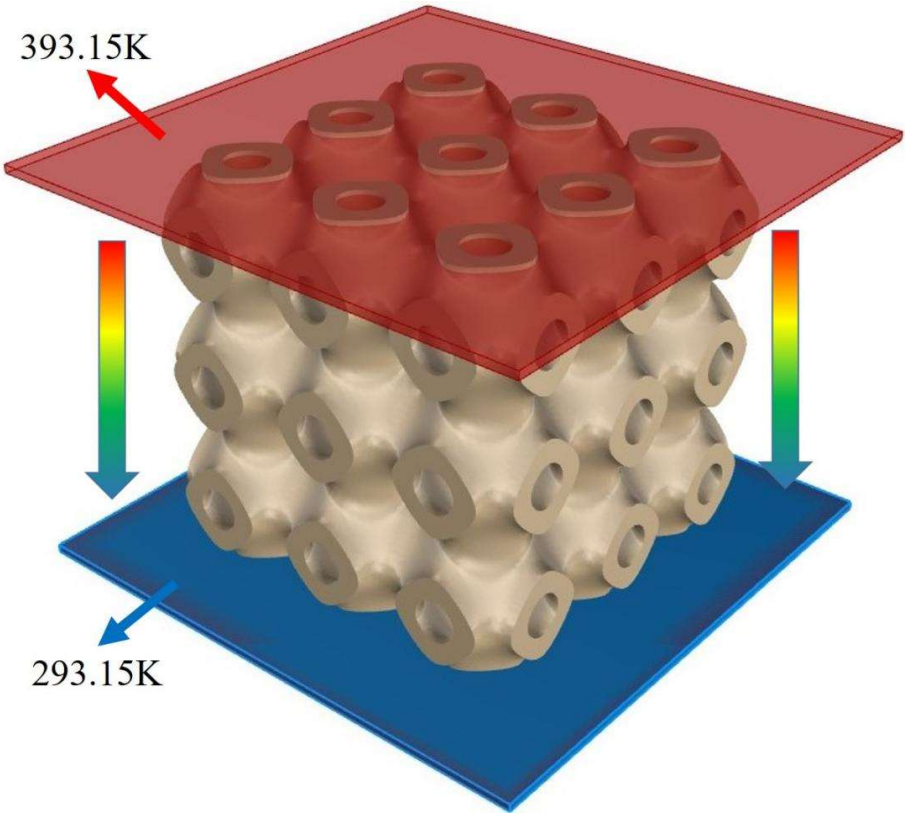

Figure 3. The heat transfer modeling of TPMS structures in vacuum

ISSN: 2414-1895 DOI: 10.6919/ICJE.202403_10(3).0015

2.3 Mesh Independence Tests

Mesh-independence verification is an important method for determining the accuracy of numerical simulation calculations. Meshing in finite element simulation is the process of discretizing the geometry into small cells with the purpose of characterizing the geometry and solving the domain. Therefore, it is necessary to minimize the error between the computationally obtained solution and the exact solution by adjusting the mesh size in a limited solution time.

The basic cell used in the meshing process in this paper is the tetrahedral cell, which has good adaptability and is particularly suitable for structures with complex geometric features. Thermal conductivity was chosen as the judging metric in performing the mesh-independent validation, and for the TPMS-P structures with 70% porosity, six sets of meshes were used to validate their mesh-independence. The mesh independence verification of the TPMS-P structure is shown in Figure 4. From the figure 4, it is easy to find that although all the effective thermal conductivities of the TPMS-P structures in vacuum environment decrease with the increase of the number of tetrahedral units, the magnitude of the thermal conductivity change is very small. The thermal conductivity of the fine mesh is 1.5384, which is lower than that of the other meshes and tends to stabilize. Considering the time cost and the accuracy of the results, the mesh size corresponding to the finer mesh is chosen as the optimal mesh size for the finite element model in vacuum environment.

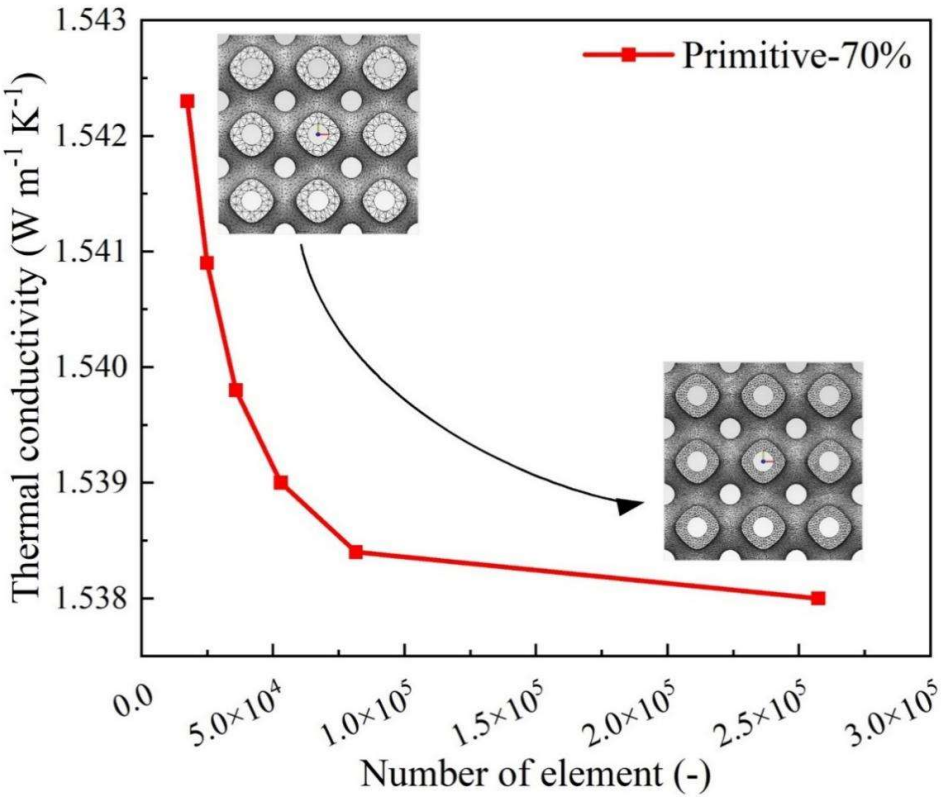

Figure 4. The mesh-independent validation results of TPMS-P structures in a vacuum environment

3. Results and Discussion

The thermal conductivity of the four TPMS structures with 70% porosity calculated by finite element simulation in steady state is shown in Figure 5. It is clear from the figure that the thermal conductivity of the TPMS-P structure is higher than the other structures, followed by the TPMS-D, TPMS-G and TPMS-I structures. This is independent of the material and is mainly due to the fact that the TPMS-P structure has a lower surface area to volume ratio, resulting in a higher thermal conductivity than the other three TPMS structures.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202403_10(3).0015

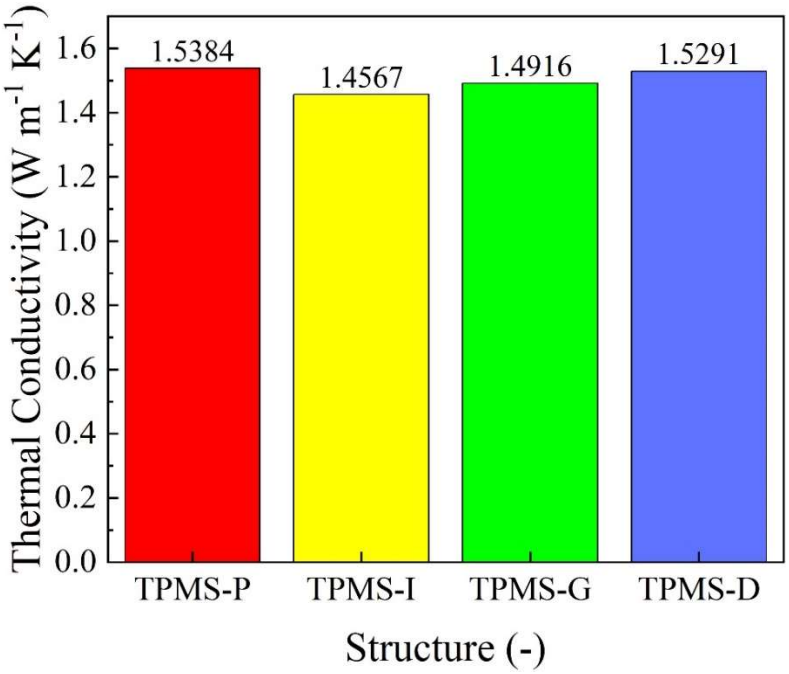

Figure 5. The thermal conductivity of four TPMS structures

In order to explore the differences in the heat transfer performance of the four TPMS structures, Figure 6 shows the temperature profiles of the four TPMS structures. It can be found that the temperature distribution of the four TPMS structures studied in this paper is more uniform, with the temperature gradually decreasing from 373.15 K to 293.15 K from the top to the bottom, which is almost isothermal in the direction of the temperature gradient. This is due to the geometric properties of the TPMS structure, which is a symmetric structure periodically arranged in three mutually perpendicular directions, which makes the heat flow transfer path very orderly, and thus the temperature distribution is more uniform.

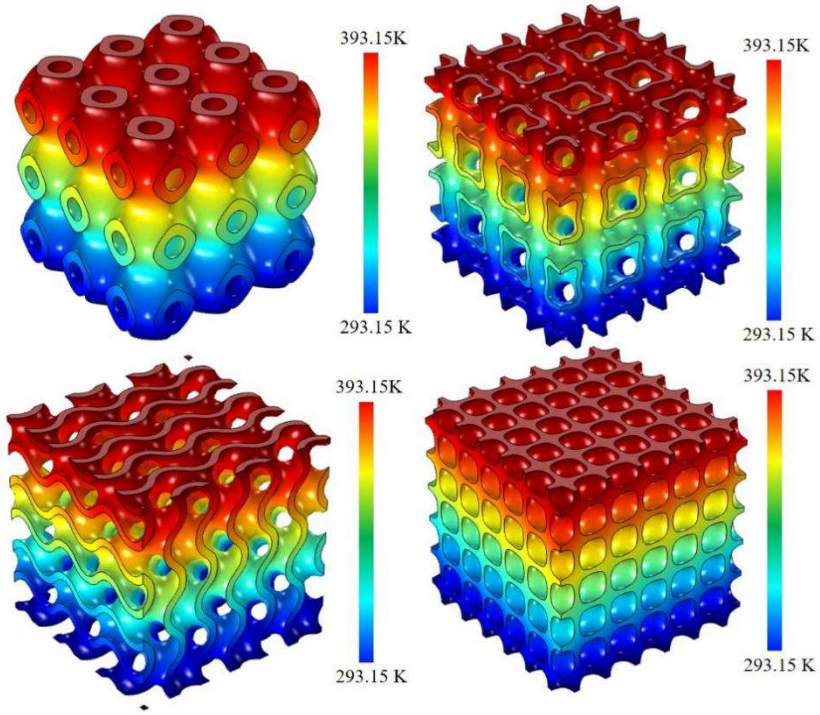

Figure 6. The temperature distribution of four TPMS structures

ISSN: 2414-1895 DOI: 10.6919/ICJE.202403_10(3).0015

4. Conclusion

In this paper, the effective thermal conductivity of the TPMS-P structure with the same porosity in vacuum environment is slightly higher than that of other TPMS structures. The reason may be that the thickness of the TPMS-P structure is larger than that of the other TPMS structures, which makes the heat transfer path shorter and wider, while the latter has more complex geometric features, which makes the path of heat transfer more tortuous, increases the total thermal resistance of the structure, and weakens the thermal conductivity of the structure. As a result of this work, heat sinks can be developed to provide new ideas for the electronics, automotive and aerospace industries.

References

[1] O. Al-Ketan, R. Rowshan, Abu Al-Rub R K. Topology-mechanical property relationship of 3D printed strut, skeletal, and sheet based periodic metallic cellular materials. Additive Manufacturing, 2018, (19): 167-183.

[2] L. Zhang, S. Feih, S. Daynes, et al. Energy absorption characteristics of metallic triply periodic minimal surface sheet structures under compressive loading. Additive Manufacturing, 2018, (23): 505-515.

[3] L. Yang, R. Mertens, M. Ferrucci, et al. Continuous graded Gyroid cellular structures fabricated by selective laser melting: Design, manufacturing and mechanical properties. Materials & Design, 2019, (162): 394-404.

[4] O B Aduda Effective thermal conductivity of loose particulate systems. Journal of Materials Science, 1996, (31): 6441-6448.

[5] G. Wang, G. Wei, C. Xu, et al. Numerical simulation of effective thermal conductivity and pore-scale melting process of PCMs in foam metals. Applied Thermal Engineering, 2019, (147): 464-472.

[6] F M Ashby The properties of foams and lattices. Philosophical Transactions Mathematical Physical, 2006, (364): 15-30.