Selective laser melting 3D printed thermal shield metamaterial structure

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Abstract. Due to ingenious design and elaborate construction of artificial structures, thermal metamaterials commonly possess extraordinary properties beyond natural materials under the conventional heat transfer conditions. Based on the transformation thermodynamics theory and the effective medium theory, in this paper, a plane-structure thermal shield aiming to manipulate heat flow was artificially designed and manufactured with the selective laser melting (SLM) 3D printing technology. The well-designed thermal shield allows the heat flow to bypass the central area of the structure for transmission and can be applied for heat protection in industries. Furthermore, the thermal shield metamaterial was fabricated and experimentally tested through the thermal monitor platform. And the experimental findings were in good agreement with the thermal simulation results. Therefore, the research results and the use of SLM 3D printing technology verified the applicability and feasibility of the thermal shield in the fields of thermal engineering and thermal control.

1. Introduction

Through artificially ingenious design and construction, the thermal metamaterials hold exceptional thermal properties beyond natural materials in the field of heat transfer. With continuous breakthroughs in the theory of thermodynamic coordinate transformation[1-3], the ingenious structural design and flexible manufacturing methods for thermal metamaterisls make it possible to achieve the adjustable non-uniform distribution of spatial thermal conductivity on engineering structures[4-8]. Therefore, the research of thermal metamaterials provides an effective and feasible method for complex macroscopic thermal control, and the research theory can be applied to thermal protection, thermal management and thermal information.[9-11].

Up to date, the current research on thermal metamaterials mainly focuses on the geometric configuration design ideas and theories to obtain abnormal thermal functional devices, such as thermal cloak and thermal concentrator.[12-14]. Besides, due to little research on related manufacturing methods, thermal metamaterials are difficult to be applied in industries. Therefore, the introduction of additive manufacturing technology provides a feasible way to achieve complex thermal metamaterials and devices, which are hard not be manufactured through traditional processing methods.[15]

In the present paper, a plane-structure thermal shield, with the thermal characteristic of bypassing the heat flow from its central area, was designed based on the transformation thermodynamics theory and the effective medium theory. Besides, the thermal shield was fabricated by SLM 3D printing technology and constructed of copper and polydimethylsiloxane(PDMS). Moreover, the designed thermal shield was thermally simulated by COMSOL Multiphysics 5.4, and the manufactured sample was thermally tested on the thermal test platform.
2. Methods and Materials

Based on the transformation thermodynamics theory\cite{1}, we chose a circular area ($r < R_2$) to demonstrate the thermal shielding effect. As illustrated in Fig. 1(a), before the coordinate transformation, the heat flow $Q$ transfers horizontally inside and outside the space $\Omega_1$. After the coordinate transformation, space $\Omega'_1$ is divided into two areas, the central area ($0 < r' < R_1$) and the ring-shaped area ($R_1 < r' < R_2$). As shown in Fig. 1(b), the heat flow $Q$ transfers along the ring-shaped area ($R_1 < r' < R_2$) and bypasses the central area ($0 < r' < R_1$), which indicates the thermal shielding effect.

Fig. 1 Schematic diagram of Coordinate transformation for the thermal shielding effect. (a) The original space; (b) The space after the coordinate transformation.

To achieve the thermal shielding effect as shown in Fig. 1, we perform the transformation coordinate as:

$$
\begin{cases}
  r' = R_1 + \frac{(R_2 - R_1)}{R_2} r \\
  \theta' = \theta
\end{cases}
$$

(1)

With acquired coordinate transformation matrix, the thermal parameters of the thermal shield after the coordinate transformation are calculated as:

$$
\begin{cases}
  k'_r = \frac{r' - R_1}{r'} \\
  k'_\theta = \frac{r' - R_1}{r'}
\end{cases}
$$

(2)

As shown in formula (2), the thermal parameters of the thermal shield are inhomogeneous and anisotropic, which cannot be satisfied by any single natural material. Thus, base on the effective medium theory\cite{16}, a particular structure composed of copper and PDMS was designed to approximately meet the thermal conductivity parameter requirements. As shown in Fig. 2, the thermal shield is composed of 5 rings, and each one consists of 2 sub-rings made of PDMS and copper respectively. Moreover, as shown in Fig. 3, outside the thermal shield is a copper plate in which small holes are distributed in hexagonal shape, and the holes are filled with PDMS. The physical parameters of copper and PDMS are listed in Table 1.

Fig. 2 Schematic diagram of Multi-layer ring-shaped thermal shield.
Table 1. Physical parameters of copper and PDMS

| Physical parameters                  | Copper | PDMS |
|-------------------------------------|--------|------|
| Density/(r, kg/m³)                  | 8960   | 970  |
| Specific heat capacity/(c, J/(kg·K))| 385    | 1460 |
| Thermal conductivity/(k, W/(m·K))   | 400    | 0.16 |
To verify the thermal shielding effect, we experimentally fabricated the thermal shield by SLM 3D printing technology. And the fabricated sample was tested on the self-built thermal test platform with an infrared heat camera (SeeK Thermal, Compact PRO). Moreover, the transient temperature fields of the fabricated thermal shield were experimentally measured from the first second until the temperature fields stabilized after 180 seconds. As illustrated in Fig.6, the temperature field images were captured at 10 seconds, 60 seconds and 180 seconds, respectively.

3.2. Discussion

The calculated thermal conductivity parameters of the thermal shield are inhomogeneous and anisotropic, which is hardly satisfied by almost any single natural material. Therefore, based on the effective medium theory that the combination of high conductivity material and low conductivity material can significantly and efficiently change the heat flow direction, we adopted copper with high thermal conductivity and PDMS with low thermal conductivity and designed a 5-layer ring-shaped structure to approximately meet the thermal parameters. And as shown in figure 5, the temperature and heat flux graphs indicate the great thermal shielding performance of the thermal shield.

Theoretically, the more layers of the ring-shaped thermal shield, the better the performance of the thermal shielding. Because as the number of layers increases, the actual thermal conductivity of the thermal shield becomes closer to the calculated value. For the same reason, the application of more kinds of material may be another effective way to improve the thermal shielding performance. However, as the structures become more complex and miniaturized, it is hard to effectively manufacture the thermal metamaterials by traditional processing methods. Thus, to overcome the processing difficulty, additive manufacturing technology was introduced in the field of thermal metamaterials. Furthermore, the experimental thermal test results of the thermal shield manufactured by SLM 3D printing technology are highly consistent with the simulation results and the design intention. Moreover, the integrated
manufacturing characteristics of additive manufacturing can effectively reduce boundary effects and improve thermal performance.

4. Conclusions
In summary, we proposed and designed a distinctive thermal metastructure - the thermal shield, which demonstrates the characteristics of bypassing the heat flow from its central area and protecting the central area from being invading by heat flow. And the multilayer ring structure composed of copper and PDMS is an effective way to achieve the thermal shield. With the application of SLM 3D printing technology, the thermal shield was fabricated and thermally tested. In addition, the thermal images of experiments have shown great agreement with the simulation thermal results and the design intention, which verified the design theory and the effectiveness and feasibility of the additive manufacturing methods. Therefore, the thermal shield has the potential to be applied in some industries, where some electronic components are susceptible to heat and demand to control the heat flow transmission. Lastly, the introduction of 3D printing technology in the field of thermal metamaterials provides an effective and feasible processing method for the development of thermal metamaterials in the direction of complexity and miniaturization.

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