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Bio-inspired tunable anisotropic thermal conductivities investigation of periodic lattice composite via external strains

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ABSTRACT

Controlling and tuning thermal conductivities of composites, including changing the direction of heat flux and thermal energy distribution, possesses significantly meaningful potential in many applications such as heat cloak, heat invisibility, heat protection and so on. In this paper, a novel design of composite metamaterial with periodic lattice structure, consisting of metal lattice layer (copper) and stretchable polymer matrix (Ecoflex), owns the ability to tune the anisotropic thermal conductivity through external strains. The parameters (such as geometric arrangement of metal lattice, loading strains), which can effectively influence the thermal properties of this metamaterial, have been investigated through finite element method considering large deformation. This new design may be helpful for designing and controlling heat flow and temperature distribution in the applications.

INTRODUCTION

Effectively manipulating the heat flow, such as controlling the direction of heat flow and propagation of thermal energy, has been of great interest in the recent decade. Directed channeling thermal energy through the dedicate design and certain arrangement of materials can significantly enhanced the utilization efficiency of the energy, which can be appropriate for battery devices, electronic devices, thermal concentrator, thermal shielding of space craft, thermal cloak, and so on.

In order to manipulate the heat flow and the temperature distribution accurately, thermal metamaterials, composed of several materials with extremely different thermal conductivities, have been put forward recently. These thermal metamaterials are used for thermal cloak, energy harvest and other purposes, and achieve remarkable effects because of the relatively large equivalent anisotropic thermal conductivities. Plenty of investigations have focused on the heat flux manipulating analysis due to the significant applications, which would be mainly focused on the effective anisotropic thermal conduction tensor of the metamaterials. Bandaru et al. developed a novelty design of two materials in terms of layered distribution in turns through theoretical analysis and experiments, which can change the direction of heat flow. Shen et al. utilized the thermal metamaterial to improve the high efficiency. A new thermal energy harvesting device was developed with thermal concentrated function via thermal metamaterials.

However, thermal properties of the metamaterials above are invariant after designed and fabricated. The tunability of thermal conductivities is the thermal properties of metamaterials can be varied even after fabricated, which can extend their applications. Stretchable structures can exactly provide the opportunity to...
reasonably engender the flexibility and change the geometric structures in the metamaterials, which can regulate the thermal characteristics. With rationale design, the elongation of stretchable electronics is more than 100%.\textsuperscript{21-24} Babaee et al.\textsuperscript{25} and Shan et al.\textsuperscript{26} designed sound metamaterials to switch and tune the wave propagation through large deformation. Herein, in order to pursue the flexibility and tunability, a new design of composite materials with periodic metal lattice embedded in polymer matrix is proposed, consisting of metal lattice layer (copper) and polymer material matrix (Ecoflex), whose thermal conductivity can be tuned through external strain with immediate effect.

This idea can also be found in the nature that nacres are consisted of microscopic aragonite tablets (95% vol.) bonded by a thin layer of organic materials (5% vol.),\textsuperscript{27} which can be recognized to be composite materials with ordered arrangement.

As shown in Figure (1a), the double-layer armor system structure in abalone shell, the hard calcite outer layer and the nacreous inner layer. Figure (1b) exhibit the scanning electron micrograph of the micro/nanostructure of natural nacre, showing that the tablets can slide under strain.\textsuperscript{28} This makes the shells own anisotropic thermal properties in different directions.

Figure (1c) shows the illustration of proposed two-dimensional periodic lattice composite material with the geometric arrangement parameters: $r_l = l_1/l_2$, in which $r_m = m_1/m_2$, $r_m$ and $r_l$ represent the distribution ratio of $x$ and $y$ direction, respectively. Let $k_1 = 400$ W/m/K and $k_2 = 0.16$ W/m/K denote the thermal conductivities of the lattice material copper and the matrix material silicone,\textsuperscript{39} respectively. In order to enhance the bonding strength of the interface between copper and Ecoflex, a thin layer of PI (<1μm)\textsuperscript{30,31} is used to fabricate a copper encapsulation layer, which is then combined with Ecoflex (e.g. Ecoflex00-10, Smooth-On, Inc, with a mixed viscosity of 14000 cps). This can effectively reduce the thermal resistance at the interface and avoid possible delamination problems during the tensile process.

For anisotropic materials, the second order thermal conductivity tensor in Cartesian coordinates system is\textsuperscript{10}

$$k_{ij} = \begin{pmatrix} k_x & 0 & 0 \\ 0 & k_y & 0 \\ 0 & 0 & k_z \end{pmatrix}. \quad (1)$$

First, considering one-dimensional parallel and perpendicular heat transport, the series thermal conductivity coefficient $k_s = (l_1 + l_2)/k_1 k_2/(l_1 k_2 + l_2 k_1)$ can be obtained for the region with the width of $m_1$ in the $x$ direction as shown in the Figure (2a).\textsuperscript{10} This region can be regarded as anisotropic material, and the thermal conductivity in the $x$ direction is $k_s$. By combining this equivalent region with the polymer matrix material with a width of $m_1$, the parallel
Then, the second order thermal conductivity tensor becomes
\[
\mathbf{k}_{\text{eff}} = \begin{pmatrix}
 k_x & 0 & 0 \\
 0 & k_y & 0 \\
 0 & 0 & k_z
\end{pmatrix}
\]
which equals to the effective thermal conductivity of metamaterials in \( x \) direction \( k_x \).

Similarly, the effective thermal conductivity of metamaterials in \( y \) direction \( k_y \) can be obtained by
\[
k_y = \frac{(m_1 + m_2)k_1k_2}{m_1k_2 + m_2k_1} \frac{l_1 + k_1l_2}{l_1 + l_2}.
\]

Then, the second order thermal conductivity tensor becomes
\[
\mathbf{k}_{\text{eff}} = \frac{(l_1 + l_2)k_1k_2}{l_1k_2 + l_2k_1} \frac{m_1 + k_2m_2}{m_1 + m_2} \begin{pmatrix}
 k_x & 0 & 0 \\
 0 & k_y & 0 \\
 0 & 0 & k_z
\end{pmatrix} \begin{pmatrix}
 (m_1 + m_2)k_1k_2 & 0 & 0 \\
 0 & (m_1k_2 + m_2k_1) & 0 \\
 0 & 0 & l_1 + l_2
\end{pmatrix}
\]
(4)

As we can see from the effective thermal conductivity tensor (Eq. (4)), the thermal conductivities \( k_x \) and \( k_y \) are influenced by three ratios: \( r_1, r_m \) and \( k_1/k_2 \). For the selected materials, \( k_1/k_2 \) is a constant value. Figure 2 shows the variation of the effective thermal conductivity \( k_x \) and \( k_y \) with the change of the \( r_1 \) and \( r_m \) ratio of the lattice composite material. When \( r_1 \) and \( r_m \) range from 0.1 to 1.0, \( k_x \) and \( k_y \) both can change from 0.2 to 1.4, reaching an order of magnitude. It should be noted that the effective thermal conductivities of two directions can be equal by choosing proper ratios.

This means that we can get the thermal metamaterial with different anisotropic effective thermal conductivities, including the isotropic and anisotropic, by designing the geometric arrangement of the lattice in the composite material.

The effects on tuning thermal conductivities via strains under specific geometric configurations are shown in Figure (1d). Strain \( \Delta a \) is applied to the \( x \) direction, and the corresponding strain \( \Delta b \) will occur in the \( y \) direction due to Poisson effect in Figure (3a). Because the elastic modulus of copper (\( E_{\text{copper}} = 140 \text{ GPa} \)) is much larger than that of Ecoflex (\( E_{\text{Ecoflex}} = 49.3 \text{ kPa} \)), the deformation of copper is negligible, the external stretching is applied on Ecoflex. On account of the incompressible Ecoflex, the following strain relations are satisfied
\[
(1 + \Delta a) \cdot (1 + \Delta b) = 1. \tag{5}
\]

\[
\Delta a = \frac{l_2}{l_1} = \Delta a \tag{6}
\]

\[
\Delta b = \frac{m_2}{m_1 + m_2} = \Delta b
\]

where \( \Delta a = \frac{\varepsilon - \varepsilon_0}{\varepsilon_0}, \Delta b = \frac{m' - m}{m}, l_2' \) and \( m_2 \) represent the length of \( l_2 \) and \( m_2 \) after deformation, respectively. The solutions of Eqs. (5) and (6) are given by
\[
\frac{l_1}{l_2} = \frac{l_1/l_2}{l_1/l_2} = \frac{l_1/l_2}{l_1/l_2} = (l_1/l_2 + 1)\Delta a + 1
\]

\[
\frac{m_1}{m_2} = \frac{m_1/m_2}{m_1/m_2} = \frac{m_1/m_2}{m_1/m_2} \cdot \left( \frac{m_1}{m_1} \right)
\]

Under the strain load, Eq. (4) becomes
\[
k'_{\text{eff}} = \begin{pmatrix}
 k'_x & 0 & 0 \\
 0 & k'_y & 0 \\
 0 & 0 & k'_z
\end{pmatrix} = \begin{pmatrix}
 \frac{m_1}{m_1 + 1} & 0 & 0 \\
 0 & \frac{m_1}{m_1 + 1} & 0 \\
 0 & 0 & \frac{m_1}{m_1 + 1}
\end{pmatrix}
\]

(8)

By solving the Eq. (7) and (8), the relationship between the effective thermal conductivity and strains can be derived.

Two-dimensional finite element analysis (FEA), which is shown in Figure (3a) and (3b), is performed via ABAQUS to study the strain distributions of metamaterials composed of copper and Ecoflex under tensile/compressive loading, and is utilized to validate the analytical model with ratio \( r_1 \) and \( r_m \) of 5 and 1/5, respectively.
FIG. 3. Finite element model of periodic lattice composite material (a) before and (b) after deformation under tensile loading. The variation of (c) the ratios ($r_l$ and $r_m$) and (d) the effective thermal conductivity ratio $k_x/k_y$ under tension and compression at a certain geometry arrangement ($r_l=5$ and $r_m=1/5$).

Figure (3c) shows the relationship between the ratios ($r_l$ and $r_m$) and elongation/shortening along $x$ direction at a certain geometry arrangement ($r_l=5$ and $r_m=1/5$). The value of $r_l$ ranges from 1 to 7.5, which initial value is 5. Meanwhile, $r_m$ ranges from 0.18 to 0.35 at an initial value of 0.2. The analytical model of deformation agrees well with FEA. The variation of the effective thermal conductivity ratio $k_x/k_y$ under tension and compression is shown in Figure (3d), with a range from 1.06 to 1.8, which is almost equivalent to the conversion from isotropy to anisotropy. This indicates that the strain applied externally is equivalent to changing the geometric arrangement of the lattice in the composite material, which is the intrinsic reason for the thermal conduction characteristics through strain.

We use this novel thermal metamaterial to the manipulation of temperature distribution in semi-annulus with inner radius of 60mm and external radius of 120mm as shown in Figure (4a), where $r_l=3$ represents the radial ratio, $r_m=1/4$ represents the circumferential ratio, respectively. Two types of semi-annular structures consisting of isotropic materials and thermometamaterials are assembled into annulus respectively that is subject to an internal pressure. Then uniform pressure is applied to the inner surface of the annular structure to make it expand isobarically. Two different configurations of the semi-annulus designed by the same geometric arrangement are obtained, which are before (Figure 4a) and after deformation (Figure 4b, with 10% deformation).

The temperature distribution of different configurations under steady state heat conduction is calculated, which are based on the configuration before and after deformation of the isotropic material and the novel thermal metamaterial. A heat source with a length of 5mm and a heat flux of 650W/m$^2$ is applied to the inner surface of the semicircle (see Fig. 4a and 4b), with 0°C initial and ambient temperature. The temperature boundary conditions at both ends are 0°C, and the rest edges are adiabatic boundary conditions. The external surface steady state temperature distribution for isotropic material and thermal metamaterial are exhibited in Figure (4g) and (4h), respectively.

For semi-annulus composed of isotropic material, the maximum temperature of the external surface before and after deformation increases from 16.9°C to 25.2°C, with a temperature increase rate of 48.9%, while that of the thermal metamaterial semi-annulus increases from 8.18 to 14.9, with a temperature increase rate of 82.8%. The temperature increase of the isotropic material semi-annulus under internal pressure is caused by the decrease of radial size caused by deformation, and the temperature increase of the thermal metamaterial semi-annulus of is caused by the following two aspects: (i) the decrease of radial size, (ii) change of the effective thermal conductivity tensor caused by the change of geometric arrangement of material under deformation.

With the internal pressure, the radial distance of the lattice material decreases and the circumferential distance increases, which leads to the increase of the effective thermal conductivity of the radial direction and the decrease of the effective thermal conductivity of the circumferential direction. This transformation will manipulate the direction of the heat flux to bend from the circumferential to the radial, which leads to the external temperature increase.

As a result, the semi-annulus composed of tunable and stretchable periodic lattice thermal metamaterial is more capable than the homogeneous semi-annulus of manipulating temperature distribution with the rate 82.8% compared to 48.9%, only under the 10% deformation.
FIG. 4. Schematic diagram of semi-annulus consisting of periodic lattice composite material of a certain geometry arrangement ($r_l=3$ and $r_m=1/4$) (a) before and (b) after deformation under uniform pressure. Distribution of temperature fields under local heating of (c) before and (d) after deformed isotropic material; (e) before and (f) after periodic lattice composite. Temperature distributions of undeformed and deformed configuration for (g) isotropic material and (h) periodic lattice composite.

CONCLUSIONS

In summary, the nacre columnar sheet inspired thermal metamaterial combines the high thermal conductivity of the lattice material (Cu) with the ductility of the matrix material (Ecoflex) effectively, making it has a tunable anisotropic thermal conductivity. The factors affecting the temperature manipulation ability of this novel thermal metamaterials are obtained through analytical expressions, which are ratio of the thermal conductivities of the homogeneous materials, geometric arrangement of metal lattice in the composite material, strains on the thermal metamaterials. The demonstration about temperature distribution manipulation ability of the semi-annulus composed of different materials shows the thermal metamaterial is a feasible option in the real time thermal manipulation based on anisotropic thermal conduction.

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