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A microlattice material with negative or zero thermal expansion

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ABSTRACT

This work presents a microlattice composite structure with a cubic unit cell that consists of twelve quarter-octahedra and describes an investigation of thermal expansion behavior of the proposed lattice material. It is assumed that all edge members of the octahedron have the same material properties and the members connecting the opposite vertices of the octahedron have different properties. Thermal expansions along the unit cell edge directions are determined by means of thermoelasticity. It is shown that the lattice material may undergo negative or zero thermal expansion with proper selection of the material and geometric properties of the microlattice members.

1. Introduction

The increasing multi-functional, structural performance requirements in aerospace, automotive, energy, electrochemical devices, biomedical and other applications have spurred the development of a new class of materials called microlattice materials [1,2]. In general a microlattice material comprises micrometer scale rod-like or bar-like members joined together at their ends. The lattice material typically has a periodic spatial arrangement of its members with high specific properties due to its cellular structural characteristics. Microlattice materials may be produced using a number of advanced manufacturing technologies such as selective laser melting, hot press molding, self-propagating photopolymer waveguides, and so on [1–3]. Applications of microlattice materials include impact engineering [4,5], thermal engineering [6–8], electrochemical devices and other applications [1,9]. Mechanical behavior of lattice materials has been studied extensively in recent years (e.g., [10,11]).

Thermal expansion of microlattice material is a concern in thermal engineering applications. Temperature gradients in the material induce thermal stresses which may contribute to degradation and even failure of the structure. One way to reduce thermal stresses at the macroscopic level is to minimize the effective coefficient of thermal expansion (CTE) of the material. Moreover, thermal stresses at the macroscopic level may be eliminated if the material is designed to achieve zero thermal expansion. Finally, a lattice material with negative thermal expansion may be integrated with (positive) thermal expansion structures to eliminate thermally induced mismatch stresses. Grima et al. [12,13] proposed a negative thermal expansion material constructed from connected triangle blocks. Lim [14,15] calculated the thermal expansion of a lattice material composed of spatial tetrahedral blocks. The above works, however, were mainly concerned with negative volume expansion and the material still expands along an edge direction of the triangular unit cell. Oruganti et al. [16] designed and fabricated a cellular structure which exhibits negative thermal expansion in a given temperature variation range. Lakes [17] envisaged a cellular solid consisting of tetrakaidecahedral foam cell with curved edges. The structure can be tuned to produce a negative CTE of unbounded magnitude. Lim [18] investigated anisotropic thermal expansion behavior of a two-dimensional microlattice structure that consists of rigid and positive thermal expansion members and exhibits positive and negative thermal expansions in two perpendicular directions. Besides microlattice materials, other forms of composites with negative thermal expansion behavior have been investigated. For example, Sigmund and Torquato [19] designed a three-phase composite with zero and negative thermal expansion using a numerical topology optimization approach. Also using a topology optimization method, Takezawa et al. [20] designed a porous planar composite structure with negative CTE and fabricated the composite by photopolymer additive manufacturing method. Hirota and Kanno [21] optimally designed a material with periodic frame structures that exhibits negative thermal expansion using a mixed integer programing technique.

This work presents a microlattice composite structure with a cubic unit cell that consists of twelve quarter-octahedra and describes an investigation of thermal expansion behavior of the proposed lattice material. Each octahedron comprises rods connecting the opposite vertices, and eight rods along the edges as shown in Fig. 1c. It is assumed that all edge members have the same properties and the members connecting the opposite vertices have different properties. Thermally induced strains and stresses in the members at the microstructural level are considered and the effective coefficient of thermal expansion of the lattice material is determined.

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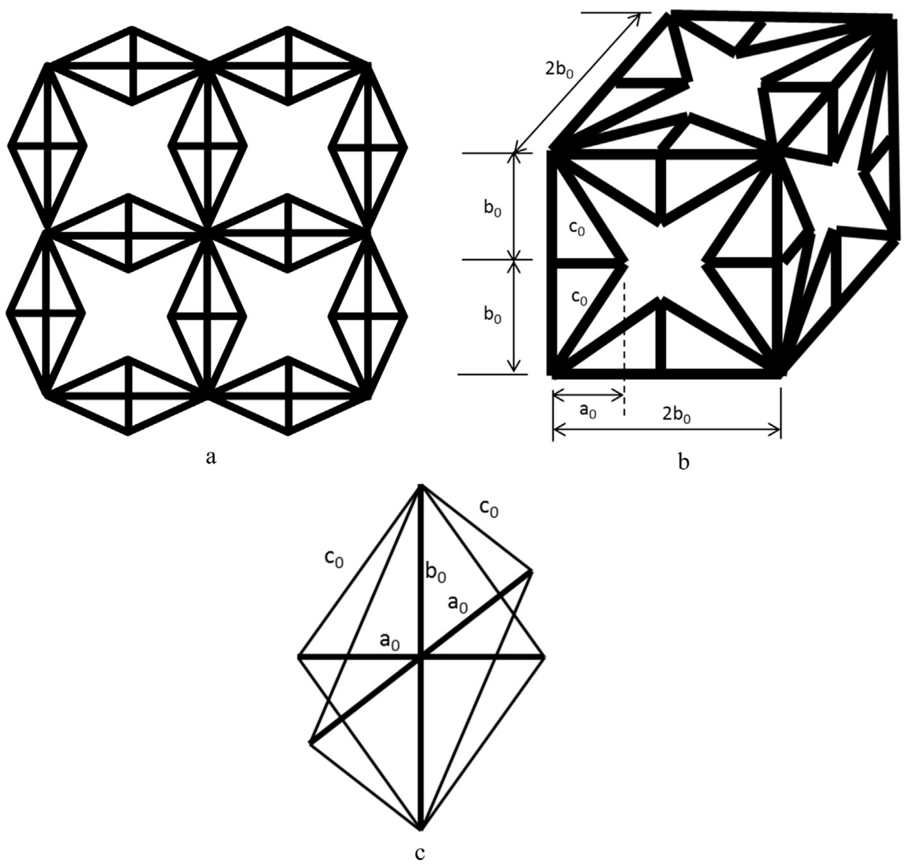

Fig. 1. (a) A microlattice material consisting of micro-rod members (front view), (b) A cubic unit cell of the microlattice material, (c) An octahedral element in the microlattice material.

2. Theoretical formulation

2.1. A microlattice material model

We consider a three-dimensional (3D) periodic microlattice material as shown in Fig. 1a (front view). A cubic unit cell of the material consisting of 12 quarter-octahedra is shown in Fig. 1b. A complete octahedron in 3D is shown in Fig. 1c. Denote by $2b_0$ the distance between the two opposite vertices (called unit cell vertices or connecting vertices) of the octahedron along the unit cell edge direction, and $2a_0$ the distance between the other pairs of opposite vertices (called free vertices). We assume that $a_0 < b_0$ so that the free vertices can move without touching the vertices of the other octahedra in the unit cell. The volume of the cubic unit cell is thus $8b_0^3$. The octahedron unit of the lattice material is made of thirteen rods of three different materials: one along the unit cell edge direction with a length of $2b_0$ (long member), four extending from the center of the long member to the free vertices, respectively, with a length of a_0 (short members) and eight with each connecting a connecting vertex and a free vertex with a length of $c_0 = \sqrt{a_0^2 + b_0^2}$ (edge members). There are no members between the free vertices.

2.2. Effective coefficient of thermal expansion

We assume that the 3D lattice material undergoes a uniform temperature variation ΔT and no mechanical loads are applied. The long member, short members and the edge members are elongated (or shortened) to $2b$, a and c, respectively, under the given conditions. Following the approach adopted in [12–15], we consider an octahedron as shown in Fig. 1c in the analysis of effective coefficient of thermal expansion. It is assumed that the relevant members are pin-connected at the free vertices and fixed-connected at other joints. Under uniform temperature variations, the members undergo only uniaxial tension/compression due to symmetry considerations.

Under the infinitesimal strain assumption, the axial strain of edge rod c can be related to those of the short rod a and long rod b as follows

$$\varepsilon_c = \varepsilon_a \cos^2\theta + \varepsilon_b \sin^2\theta \tag{1}$$

where subscripts a, b and c denote the types of members (short, long and edge, respectively), and the angle θ is defined by

$$\theta = \tan^{-1}(b_0/a_0) \tag{2}$$

Using Hooke's law, the axial strains are related to the axial stresses in the members and the temperature variation by [22]

$$\varepsilon_a = \frac{\sigma_a}{E_a} + \alpha_a \Delta T,$$
$$\varepsilon_b = \frac{\sigma_b}{E_b} + \alpha_b \Delta T,$$
$$\varepsilon_c = \frac{\sigma_c}{E_c} + \alpha_c \Delta T \tag{3}$$

where σ stands for the axial stresses, E Young's modulus, α the coefficient of thermal expansion (CTE). Substituting Eq. (3) into Eq. (1) gives

$$\frac{\sigma_c}{E_c} - \frac{\sigma_a}{E_a}\cos^2\theta - \frac{\sigma_b}{E_b}\sin^2\theta = \alpha_a \Delta T \cos^2\theta + \alpha_b \Delta T \sin^2\theta - \alpha_c \Delta T \tag{4}$$

The equilibrium at the free vertices gives

$$\sigma_a A_a + 2\sigma_c A_c \cos\theta = 0 \tag{5}$$

where A denotes the cross sectional area of the rod. Similarly, the equilibrium at the connecting vertices is (we assume the thermal stresses in a unit cell are self-balanced)

$$\sigma_b A_b + 4\sigma_c A_c \sin\theta = 0 \tag{6}$$

Solving Eqs. (4) to (6) for the three stresses, we have