Journal of the Mechanics and Physics of Solids 86 (2016) 173–191

Contents lists available at ScienceDirect

Journal of the Mechanics and Physics of Solids

journal homepage: www.elsevier.com/locate/jmps

Planar lattices with tailorable coefficient of thermal expansion and high stiffness based on dual-material triangle unit

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ARTICLE INFO

Article history:
Received 10 June 2015
Received in revised form
23 September 2015
Accepted 12 October 2015
Available online 20 October 2015

Keywords:
Lattice material
Thermal expansion
Mechanical properties
Aperiodic lattice

ABSTRACT

The unexpected thermal distortions and failures in engineering raise the big concern about thermal expansion controlling. Thus, design of tailorable coefficient of thermal expansion (CTE) is urgently needed for the materials used in large temperature variation circumstance. Here, inspired by multi-fold rotational symmetry in crystallography, we have devised six kinds of periodic planar lattices, which incorporate tailorable CTE and high specific biaxial stiffness. Fabrication process, which overcame shortcomings of welding or adhesion connection, was developed for the dual-material planar lattices. The analytical predictions agreed well with the CTE measurements. It is shown that the planar lattices fabricated from positive CTE constituents, can give large positive, near zero and even negative CTEs. Furthermore, a generalized stationary node method was proposed for aperiodic lattices and even arbitrary structures with desirable thermal expansion. As an example, aperiodic quasicrystal lattices were designed and exhibited zero thermal expansion property. The proposed method for the lattices of lightweight, robust stiffness, strength and tailorable thermal expansion is useful in the engineering applications.

1. Introduction

Materials and structures used in applications such as aerospace, precision instruments and civil engineering are susceptible to suffer large temperature variation and sensitive to thermal distortion (Song et al., 2011). Actually, for satellite antenna and its supporting structures utilized in aerospace, thermomechanical failure always occurs due to excessive thermal distortion resulted from the thermal cyclic of orbiting satellite (Jacquot et al., 1998). Therefore, materials and structures with tailorable, especially zero coefficient of thermal expansion (CTE) are urgently needed.

At present, the available range of CTE in engineering materials is quite narrow. To obtain wide range of CTE, most of current researches are mainly concentrated on bulk materials and composites. Few of bulk materials, such as antiperovskite manganese nitrides (Takenaka and Takagi, 2009), metal oxides (Allen and Evans, 2003), zirconium tungstate (Lind et al., 2011) etc. have been founded with negative thermal expansion. However, their generalized mechanism is not yet understood and synthesizing these materials for engineering applications is not available (Miller et al., 2009). The intrinsic brittleness of Zerodur limits its applications in structural engineering and the Invar only retains low CTE under 0–100 °C (Steeves et al., 2007). Although fiber-reinforced composites have tailorable CTE due to low or negative axial thermal expansion of their fibers

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http://dx.doi.org/10.1016/j.jmps.2015.10.004
0022-5096/

(Ito et al., 1999; Kelly et al., 2006; Rangarajan et al., 2011), large difference of CTEs between the fiber and matrix leads to interface thermal strain and failure. Sigmund and Torquato (1996, 1997), Chen et al. (2001) and Wang et al. (2011) employed optimization methods to achieve zero thermal expansion and maximum stiffness for three-phase composites. However, the complicated geometries hinder the practical manufacture and applications.

Thus, it is important to integrate tailorable CTE with lightweight and robust mechanical properties for the materials. To achieve tailorable CTE, Lakes (1996, 2007) initiated the design of macroscale lightweight lattice materials which were assembled through dual-material members (Lehman and Lakes, 2013). Jefferson et al. (2009) proposed honeycomb-like hybrid lattices which were composed of inner triangle and outside honeycomb. Lim (2005, 2011) described a re-entrant honeycomb with negative thermal expansion. Above lattices obtain tailorable CTE through bending-dominated members and display less stiffness compared with stretch-dominated lattices. Moreover, the complicated geometrical connections of the members lead to manufacture complexity. Dual-material triangle lattice presented by Miller et al. (2008) exhibits tailorable CTE. This stretched-dominated triangle lattice can be used as the basic unit to construct other lattice configurations such as the near zero thermal expansion lattice structures (Palumbo et al., 2011) and the planar lattices (Steeves et al., 2007; Toropova and Steeves, 2014). However, all of studies only investigated individual special cases of periodic lattice configurations. The underlying geometrical rules between different lattices have not been reported. Moreover, most of designed lattice materials were not yet experimentally verified. Most importantly, currently, there is no generalized design method to construct arbitrary periodic and especially aperiodic lattices for tailorable thermal expansion characteristics.

The main contributions of this paper are the planar lattice design and a novel stationary node method. These designed planar lattices exhibit tailorable thermal expansion and high specific biaxial stiffness. Fabrication process, established measurement setup as well as thermal expansion measurements from experiments are provided to demonstrate the effectiveness of the planar lattice design. A generalized stationary node method is proposed to reconstruct periodic and aperiodic lattices for desirable thermal expansion. The paper is arranged in following manner:

In Section 2, as the basis of the planar lattice design, mechanism of tailorable CTE for dual-material triangle lattice is briefly introduced. Periodic planar lattices with isotropic tailorable CTE are designed inspired by crystallography. Thermal expansion behavior and biaxial stiffness of the planar lattices are analytically discussed. The details of performed

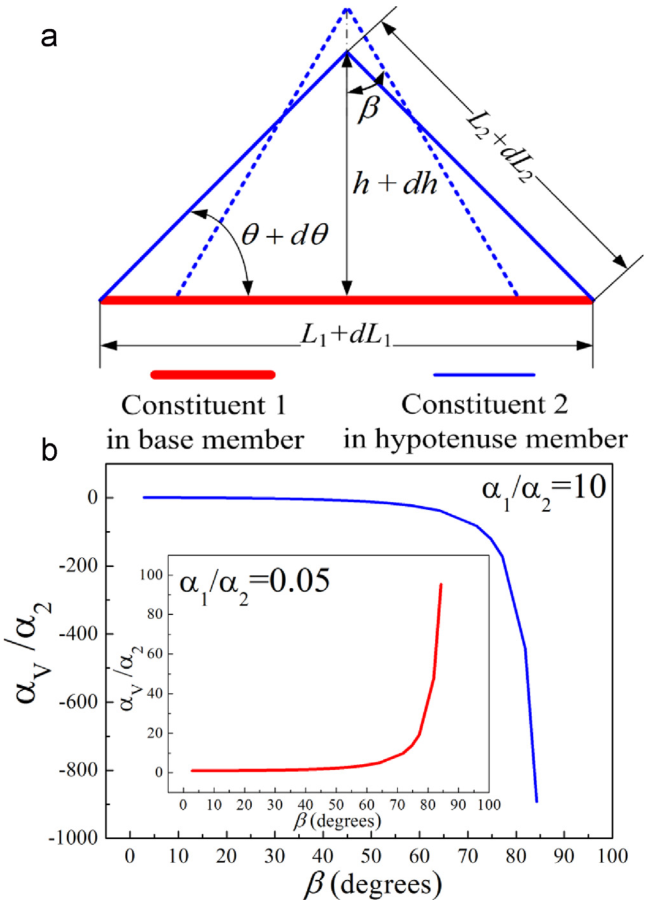

Fig. 1. Thermal deformation mechanism of dual-material triangle lattice: (a) constituent 1 has CTE α_1, while constituent 2 has CTE α_2; and (b) zero and negative CTE are available with $\alpha_1 > \alpha_2 (\alpha_1/\alpha_2 = 10)$, while large positive CTE are available with $\alpha_1 < \alpha_2 (\alpha_1/\alpha_2 = 0.05)$.