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An investigation of the mechanical behavior of three-dimensional low expansion lattice structures fabricated via laser printing

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ABSTRACT

A feasibility study of the fabrication of a specific type of low expansion lattice structure via 3-D laser printing has been conducted. In addition, a detailed baseline understanding of the mechanical response of a specific low thermal expansion lattice geometry has been established. The printed Ti-6Al-4V structures exhibit robust mechanical behaviour and fail via initial buckling followed by strengthening and then fracturing of the struts. Finite element simulation can predict the mechanical behaviour of the printed structures with a good degree of accuracy until the onset of buckling, which is the first point of failure. An analytical model has also been constructed, and homogenization techniques have been implemented to determine the effective stiffness and strength of the lattice structure arranged periodically to be used in sandwich panels. The analytical studies of the lattice structure performance show that the low CTE lattices are suitable for lightweight applications. Additionally, analysis has been performed to optimise the design of a bi-material lattice structure and the optimised design was found to have better performance compared to the bulk material while maintaining a low coefficient of thermal expansion for most cases studied. The techniques used in this paper can serve as a foundation for future studies to optimise and improve such lattice structures.

1. Introduction

Low thermal expansion lattices that also exhibit lightweight and high stiffness show great promise as structural components in applications where controlled thermal expansion is an important consideration. Examples include hypersonic vehicles (where frictional heating can lead to large temperature gradients which can impose substantial thermal stresses on underlying structures and components), space mirrors, telescope arrays and structural heat pipes. An example of such a lattice designed at the University of California Santa Barbara is shown in Fig. 1 [1]. The lattices consist of two components: (i) a structural framework made from a material with a low coefficient of thermal expansion (CTE), and (ii) separate triangular inserts comprised of a material with a higher CTE. By varying the lattice geometry (skew angle, , shown in Fig. 1) the lattice can be engineered to exhibit desired thermal expansion characteristics. The exact mechanism by which this is achieved has been described in detail elsewhere [1,2]. However, summarised very briefly, the triangular inserts push against the lattice framework during heating, causing rotation of the framework struts at invariant nodes. In this way, the framework expands into the open spaces of the lattice and the lattice as a whole remains dimensionally constant.

Significant research has already been carried out on two-dimensional bi-metallic lattices. The controlled CTE capability has been demonstrated successfully [1–2]. However, the functionality of such lattice structures could be substantially improved if extended to three dimensions. The concept of lattice structures of this nature is not new had have been the subject of many studies [3–10]. Palumbo et al. [3] measured the thermal expansivity of monolithic and bi-material 2-D lattice geometries and found good agreement with analytical predictions. Lehman and Lakes [4] designed lattices that achieve controlled CTE via either the Poisson effect or a curved bi-material rib morphology. In addition, the effects of multi-level hierarchy on the specific stiffness of low CTE lattices have been investigated by Xu et al. [5]. Wei et al. studied planar triangular high stiffness, low CTE lattices similar to the one presented in Fig. 1 [6] and also lightweight 3-D bi-pyramidal structures [7]. Lightweight metamaterials with tunable negative thermal expansion in three directions have been reported by Wang et al. [8]. Mukhopadhyay and Adhikari have employed probabilistic and analytical frameworks to study the stochastic mechanics of metamaterials [9] and the elastic moduli of quasi-random spatially irregular hexagonal lattices [10]. However, the extension of this particular type of low thermal expansion lattice geometry to three dimensions has not

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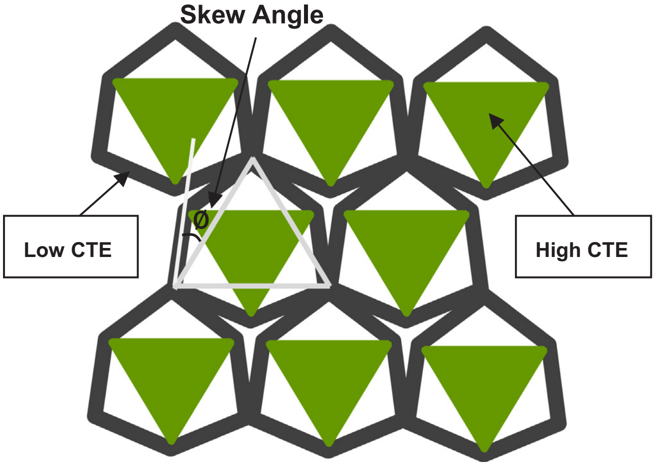

Fig. 1. Schematic illustration of a low thermal expansion lattice structure (designed by UCSB [1]).

been investigated previously and could facilitate the creation of complete 3-D structures that would exhibit the same controlled thermal expansion characteristics as the 2-D lattices previously explored. Additionally, the 3-D lattices can be manufactured and used in sandwich panels or similar structures, serving as a multifunctional lightweight structural component. Sandwich panels of this type using composite truss cores have been successfully fabricated (using techniques such as thermal expansion molding and snap-fitting of carbon fiber reinforced polymer laminates) and studied in a number of previous works [11–13]. However, manufacturing can often be challenging and expensive using conventional manufacturing techniques. The additive manufacturing technique of 3-D laser printing offers a viable and convenient way of fabricating three-dimensional adaptations of these types of lattice structures. A number of studies involving the 3-D printing of lattice structures have been conducted previously [14–19]. However, the type of lattice structure presented in this paper has been designed to exhibit controlled thermal expansion. As a result, such structures are not optimized for mechanical performance. This issue has not been specifically addressed in previous studies of 3-D printed lattices. An illustration of a theoretical 3-D low expansion lattice, also devised at the University of California Santa Barbara [1], is shown in the CAD drawings presented in Fig. 2. It consists of a skewed tetrahedral framework with octahedral inserts. The purpose of this investigation was, therefore, to try to fabricate actual 3-D structures similar to that shown in Fig. 2 via laser printing and then to evaluate the mechanical behaviour of the printed structures. It should be noted that the loading mode during heating mentioned earlier, namely the strut rotation at invariant nodes as a consequence of the thermal expansion of the inserts, will be different to that involving an external applied mechanical stress such as uniaxial compression.

In this study, a finite element model will be constructed to show the deformation mechanism of the three-dimensional lattice structure, which is then compared against the experimental results. Apart from that, the lattice structures are intended to be used as structural components, for example in sandwich panels, and therefore it is crucial to be able to predict important mechanical properties of the lattice material. Therefore, homogenization techniques, using analytical calculations, are then applied in this study to determine the effective stiffness and strength at the onset of failure of these structures after demonstrating that the analytical solutions are sufficiently accurate up until the onset of plastic deformation or buckling of the lattice. The findings in this paper aim to improve the understanding of 3-D printed lattice structures and analysis framework to predict important mechanical properties of low-CTE lattice structures and other lattice structures in general.

2. Experimental procedure

The first part of the program involved using the computer-aided design (CAD) software Rhinoceros (Robert McNeel & Associates) to produce CAD drawings of 3-D lattices based on the illustration in Fig. 2. Initially, the lattice unit cell was constructed within the software (Fig. 3(a)) and then multiple unit cells were used to build complete 3-D lattice structures (Fig. 3(b)).

The drawings were converted to STL files which were then opened using a dedicated application called Magics (Materialise Software). This software has two primary functions: (a) to position and orient the 3-D structure correctly for printing and (ii) to generate vertical support struts. (Without support struts, any lattice members that are inclined at an angle of less than 45° to the horizontal would collapse during fabrication.) Finally, Magics is used to create a slice file (essentially the part is divided into many horizontal slices). This file is used by the laser printer itself for the actual fabrication of the part.

At this stage, the goal was simply to assess the viability of using laser printing to fabricate the basic lattice geometry from a single material (Ti-6Al-4V). In addition, it was considered sufficient to fabricate

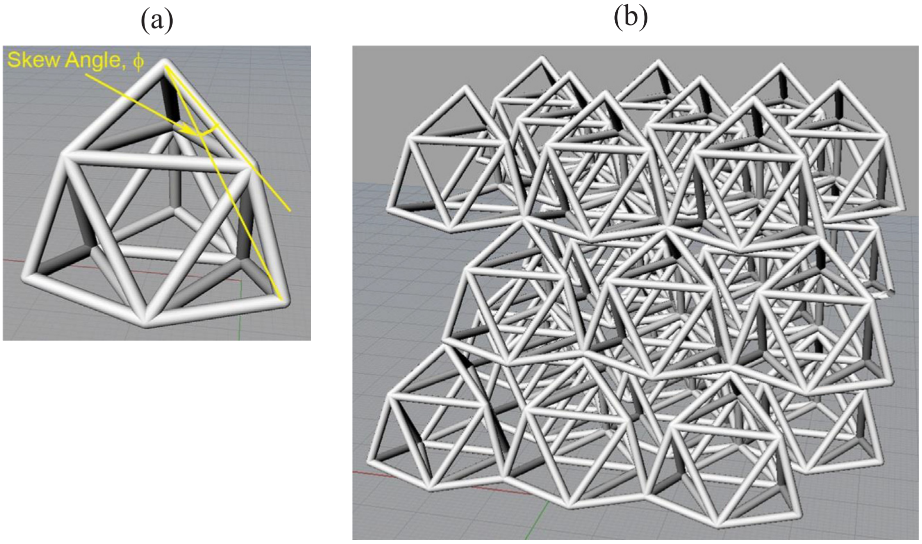

Fig. 2. CAD drawings of three-dimensional low expansion lattice structures; (a) single unit cell, and (b) complete 3 × 3 × 3 lattice.

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