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積層造形最前線

Analysis of Functional Lattice Structures Fabricated via Additive Manufacturing

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Abstract:

Functional lattice structures or metamaterials are cellular structures that are designed to exhibit a particular physical or mechanical property. Laser printing or additive manufacturing is an excellent choice of manufacturing process for the fabrication of functional lattice structures. With the selection of appropriate starting materials (powders), additive manufacturing is capable of printing high integrity structures with complex geometries. The technique is also significantly more material and energy efficient (green) than many conventional manufacturing methods.

Two functional lattice structures fabricated via 3-D laser printing are discussed in this article. The first is a structure designed to exhibit low thermal expansion behavior, while the second is an auxetic (negative Poisson's ratio) metamaterial. The details of the laser printing process are first described followed by an account of the mechanical response of each type of structure.

要旨

機能性ラティス構造やメタマテリアルは、特有の物理的・機械的特性を示すように設計されたセル構造である。そして、レーザープリンティングや積層造形は、機能性ラティス構造を構築するのに優れた製造プロセスである。適切な原材料（粉末）を選択して積層造形することで、複雑な形状をした完成度の高い構造を印刷できる。多くの従来の製造方法よりも、この技術は材料効率とエネルギー効率が大幅に優れている。

本論文では、三次元レーザープリンティングによって作製された2つの機能性ラティス構造について解説する。1つ目は低熱膨張挙動を示すように設計された構造であり、2つ目はオーセティック（負のポアソン比）を有するメタマテリアルである。レーザープリンティングプロセスをまず詳述し、続いてそれぞれの構造の機械的応答について解説する。

1 Introduction

Lattice structures (sometimes called metamaterials) are designed to exhibit properties or functionality not typically found in naturally occurring or bulk materials. They generally consist of repeating unit cells and can be two or three dimensional. The unique properties can be mechanical, physical, optical or electronic in nature or even a combination of these. It is possible to maximize the properties by careful engineering or optimization of the lattice geometry. However, in order for the desired properties to be realized, the required lattice geometry can be quite complex and intricate. In addition, in some cases, the unit cell size of the structure can be very small (sometimes on the micrometer scale). Fabricating such structures via conventional manufacturing methods such as machining or lost wax casting can often be very expensive, difficult and energy inefficient. In some cases, it may be virtually impossible to produce such structures via conventional techniques. Additive manufacturing offers a way of fabricating complex functional metamaterials in a much more cost effective, and material/energy efficient or "green" manner[1). The method of 3-D printing employed in this work is called selective laser melting (SLM) and also laser powder bed fusion (LPBF). The basic principle of the technique involves the melting of a thin layer of metal powder by a high-power laser (95W, for this investigation) in a specific geometric pattern (controlled by computer software). The process is repeated and the 3-D structure is built up layer by layer. Typical layer thickness is around 25 μm.

This article will introduce two types of three-dimensional functional lattice structure or metamaterial fabricated from either titanium or stainless steel powder via SLM. The properties and mechanical behavior of each 3-D printed lattice structure will then be discussed.

The first type of lattice presented is designed to exhibit low or even zero thermal expansion behavior. Two-dimensional structures of this type have potential applications in the skin of hypersonic vehicles (where frictional heating can impose significant thermal stresses on underlying components). When extended to three dimensions, applications include space mirrors, telescope arrays or any other situation where low or controlled thermal expansion is desirable. The unit cell of the lattice structure is a bi-metallic arrangement of two components: (i) an outer framework of skewed tetrahedral unit cells composed of a material with a low coefficient of thermal expansion (CTE), such as titanium; and (ii) octahedral inserts made from a material with a high CTE, such as aluminum. The concept is illustrated in Fig.1 and was derived from a very similar 2-D low thermal expansion lattice designed at the University of California Santa Barbara (UCSB)[2,3).

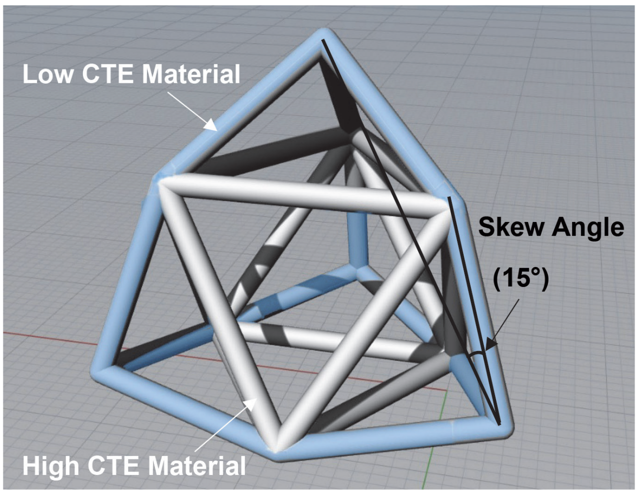

Fig.1 Unit cell of 3-D low thermal expansion lattice structure. The outer framework and octahedral insert are composed of materials with a low and high CTE, respectively. (Online version in color.)

The second type of functional lattice structure presented in this article is an auxetic metamaterial. The term "auxetic" means that the material or structure in question exhibits a negative Poisson's ratio (NPR)[4). Consequently, an auxetic material or structure will expand laterally when deformed in tension and contract laterally under compression. One of the main advantages of auxetics is superior energy dissipation during impact[5) and this makes them excellent candidates for crash protection structures in aerospace or ground transport applications. The most common type of auxetic geometry is called a re-entrant geometry and is shown in Fig.2. It is the type of auxetic geometry that was studied in the presented work.

2 Mechanical Evaluation of 3-D Printed Low Thermal Expansion Lattices

The unit-cell geometry of the 3-D bi-material low thermal expansion lattice is shown in Fig.1. The mechanism by which low thermal expansion is obtained has been discussed in detail elsewhere[2,3). However, summarized briefly, as the lattice is heated, the high CTE material inserts push against the lower CTE framework causing rotation of the framework struts at invariant nodes (the vertices of the tetrahedra). In essence, the structure expands into the open spaces between the unit cells. By varying the skew angle (the deviation angle of the struts from an equilateral triangle - shown in Fig.1), it is possible to tailor the overall CTE of the lattice. Zero or even negative CTE is possible with high skew angles (typically 25° or greater). However, for practical applications, a low but positive CTE that matches the thermal expansion of the lattice to that of underlying (typically cooler) components is generally preferred.

The research discussed here involves purely the evaluation of the mechanical response of the low CTE lattice structure. Verification of the low CTE behavior of the lattices has been previously accomplished at UCSB[2,3). Consequently, it was sufficient to fabricate the lattice structures from a single material to make fabrication via 3-D printing easier.（However, it should be noted that it is now possible to print two materials simultaneously.）Engineering drawings of the 3-D geometric concept shown in Fig.1 were produced using the CAD software Rhinoceros,（Robert McNeel & Associates）. Single unit cells were produced initially and then complete lattice structures, comprised of 3 ×3×3 arrays of unit cells.

The CAD drawings were then converted to “slice” files by using special software called Magics, and the slice files are uploaded to a Concept Laser Mlab cusing R 3-D laser printer（Concept Laser GmbH, Lichtenfels, Germany）. The Magics software also automatically adds support struts to the structure where necessary. Without support, any lattice strut or element at an angle of less than 45° to the horizontal would simply collapse during the SLM operation. The lattices structures（both single unit cells and 3×3×3 arrays）were then printed from Ti-6Al-4V powder. The powder size is typically 10 -50 μm and can be sieved if a narrower range of particle size is desired. Ti-6Al-4V was chosen because it is a well-known aerospace alloy with excellent specific strength. Printing a complete 3×3×3 three-dimensional low expansion lattice structure can take up to 24 hours but the process is completely autonomous once it has commenced. Following printing, the support struts were manually removed with wire cutters. This can be a difficult and labor-intensive operation for complex structures such as these lattices. The printed complete 3 ×3×3 array is shown in Fig.3. Some metallic materials are sensitive to warping and cracking following 3-D printing as a result of residual stresses caused by the rapid solidification of the material following laser melting. Titanium alloys are one such class of materials. However, by keeping the strut thickness relatively low（1.5 mm）residual stress could be minimized. In addition, the finished structures were subjected to a stress relieving heat treatment of 840℃ for 2 hours following by furnace cooling.

A metallographic section of one of the struts is shown in Fig.4. It is clear from the image that the printed material is dense with very little porosity. Hence, this type of additive manufacturing is very capable of printing functional lattice structures of this type with a high structural integrity.

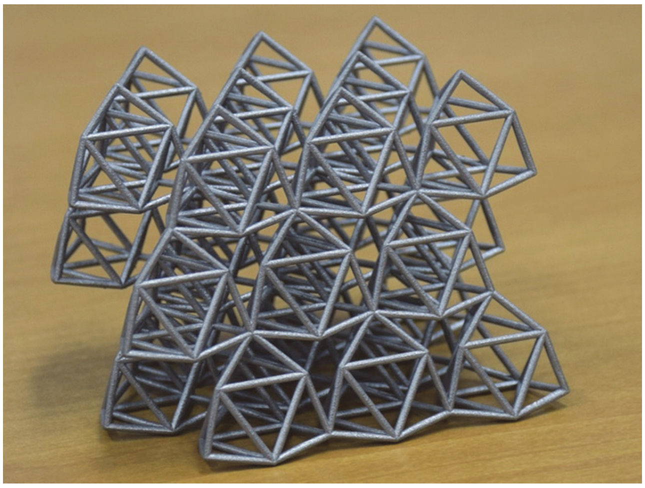

Fig.3　Metallic laser printed 3-D low thermal expansion lattice structure consisting of a 3×3×3 array of unit cells.（Online version in color.）

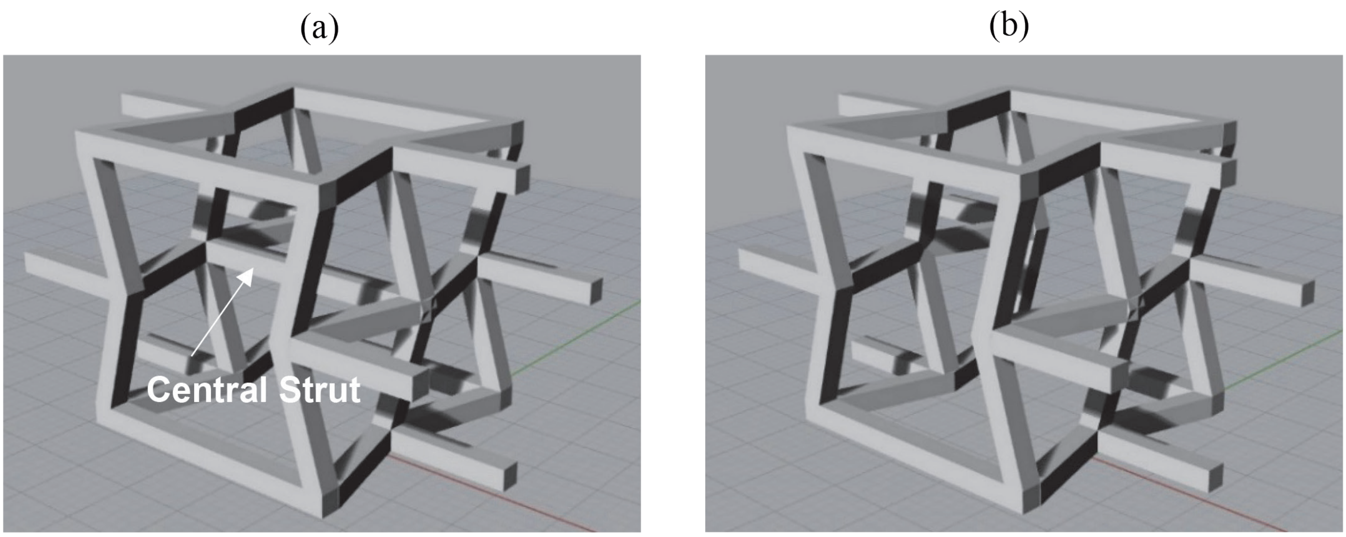

Fig.2　Auxetic re-entrant unit cells; (a) central strut present, (b) central strut removed.（Online version in color.）

Following 3-D printing, the mechanical response of the lattice geometry under uni-axial compression could be investigated. For simplicity, compression tests were performed on individual unit cells that were supported at the three bottom corners as shown in Fig.5. This was done to simulate the loading configuration of a multi-cellular lattice. The experiments were conducted under displacement control using a displacement rate of 1 mm/min until complete failure of the specimen occurred. Incremental deformation as a result of increasing compressive strain is also shown in Fig.5. The sequence of events comprising the total failure of the unit cells is illustrated graphically on the load-strain curve shown in Fig.6. As can be seen in Fig.6, initially the structure behaves in a linear elastic manner until the first load peak which corresponds to the buckling of the top three struts in the unit cell. Following buckling, the three struts fracture and the load drops significantly. The load then starts to increase again when the upper platen contacts the remaining (bottom) part of the unit cell. The curve then reaches a second load peak corresponding to the buckling and subsequent fracture of the lower struts.

Finite element simulations were able to accurately predict the experimental compression behavior up to the point at which the platen contacts the bottom part of the unit cell following the fracture of the top three struts. However, beyond this point, the simulations deviate from the experimental observations. The reasons for the deviation are thought to be primarily a combination of slipping of the

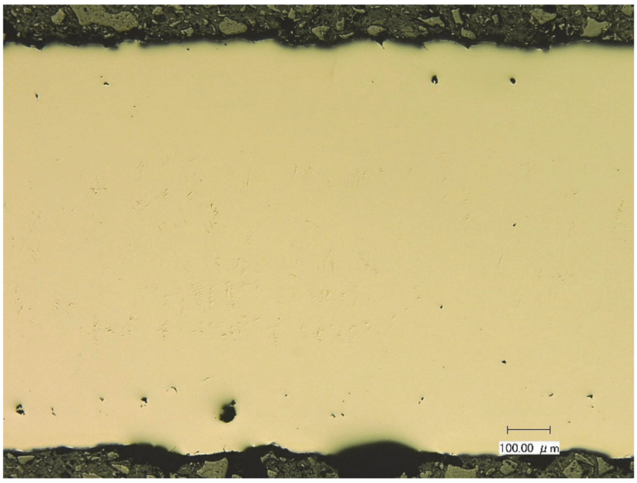

Fig.4 Metallographic section of 3-D low thermal expansion lattice strut. (Online version in color.)

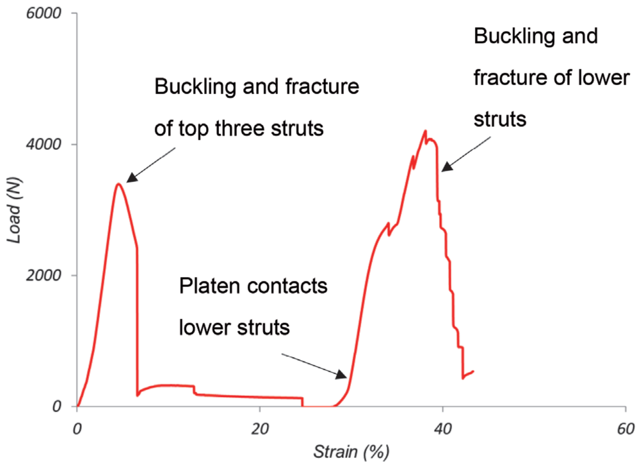

Fig.6 Compressive quasi-static load-strain curve for 3-D low thermal expansion lattice unit cell (compressed as shown in Fig. 5). (Online version in color.)

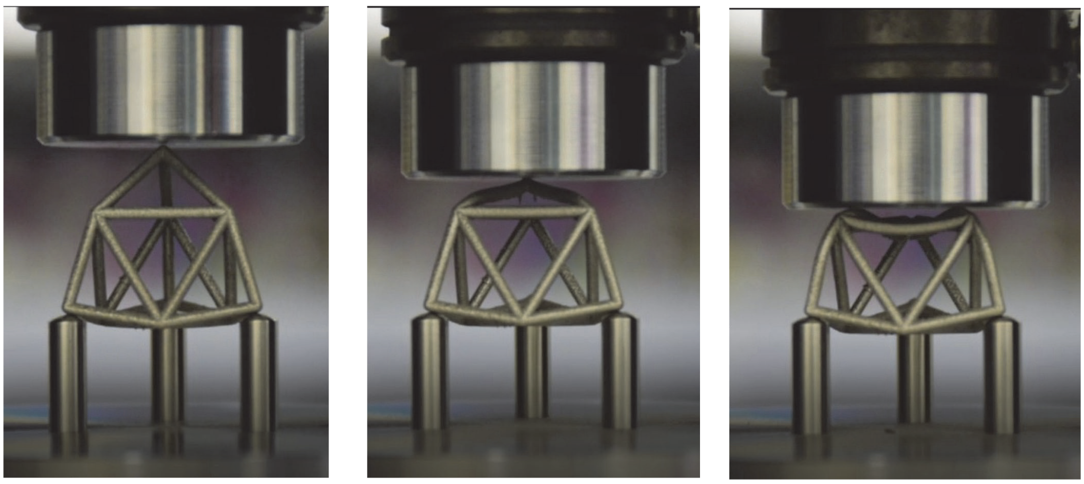

Fig.5 Incremental deformation of 3-D low thermal expansion unit cell with increasing compressive strain. (Online version in color.)

unit cell on the 3-point loading fixture and also the fact that the simulations did not account for fracture of the lattice struts under compression.

Finally, homogenization studies determined that under optimum conditions the structures have comparable effective strength and stiffness to lightweight beams and panels.

The investigation has shown that this 3-D low thermal expansion lattice structure is robust under mechanical loading, and therefore, in addition to providing controlled thermal expansion, the mechanical performance is sufficient for use in structural engineering applications.

3 Investigation of the Mechanical Response of 3-D Printed Auxetic Metamaterials

The re-entrant auxetic geometry studied in this investigation is shown in Fig.2. Negative Poisson's ratio is achieved by the "hinge" movement of the（diagonal）re-entrant struts at the nodes. The same laser printer used for the 3-D low expansion lattice（above）was also employed in this study. However, in this investigation, the structures were printed from stainless steel powder. Stainless steel was chosen because it is relatively easy to print and（unlike titanium alloys）does not typically exhibit residual stress-induced warping or cracking.

Two types of structure were produced. The first is a lattice in the strict definition of the term and features a strut in the center of the unit cell（Fig.2（a））. In the second type of structure, this strut has been removed（Fig.2（b））. The latter configuration（although no longer strictly a lattice）is still a re-entrant structure capable of NPR behavior and has the added advantages of reduced weight and easier removal of support struts following 3-D printing. However, as will be shown, stiffness of the structure will be comprised in the direction parallel to this strut. In addition, structures were fabricated with 5 mm thick constraining walls on the bottom and sides of the structures. The purpose of these walls was to allow investigation of the effect of boundary constraint on the auxetic behavior of the lattices. It is expected that added constraint may compromise the NPR effect. The final printed metamaterials are shown in Fig.7.

Following successful fabrication, the mechanical and auxetic response of the structures was studied. As in the case of the low thermal expansion structures（above）, experiments were carried out under quasi-static compression loading but for the auxetic lattices, a displacement rate of 0.2 mm/min was used. The slower displacement rate was chosen to allow more precise evaluation of the NPR effect. Experiments were conducted with the stress axis parallel to the short and long axes of the specimen, designated y-axis and z-axis, respectively（as shown in Fig.7（b））.

The results of the quasi-static compression experiments for the unconstrained structures are presented in Fig.8. For these experiments, the whole specimen was compressed（referred to as whole area compression.）It is evident that when the compressive stress is applied in the y-axis direction, the removal of the central strut from the unit cell has virtually no effect on the mechanical response（Fig.8（a））. However, the effect is significant when the stress is applied in the z direction; removal of the central strut decreases the elastic modulus of the structure by almost

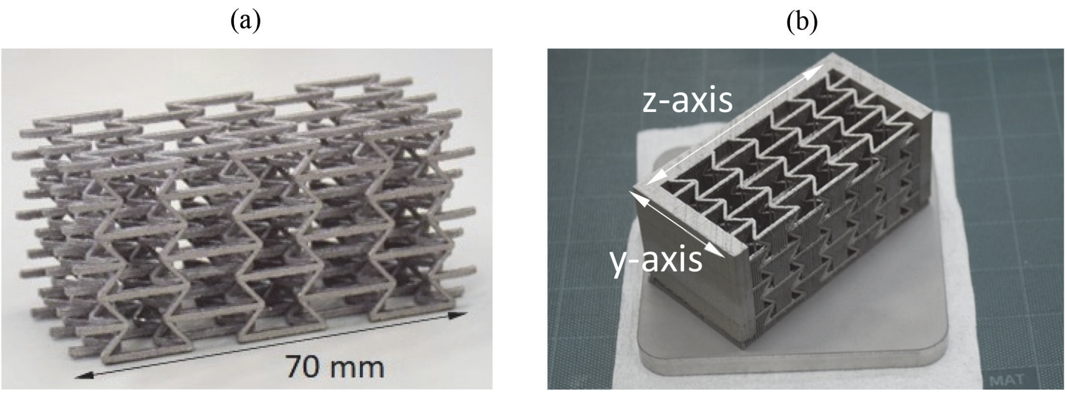

Fig.7 Laser printed 3-D auxetic re-entrant metamaterials; (a) unconstrained, (b) following the addition of thick constraining walls. (Dimensions and axis designation shown.)（Online version in color.）

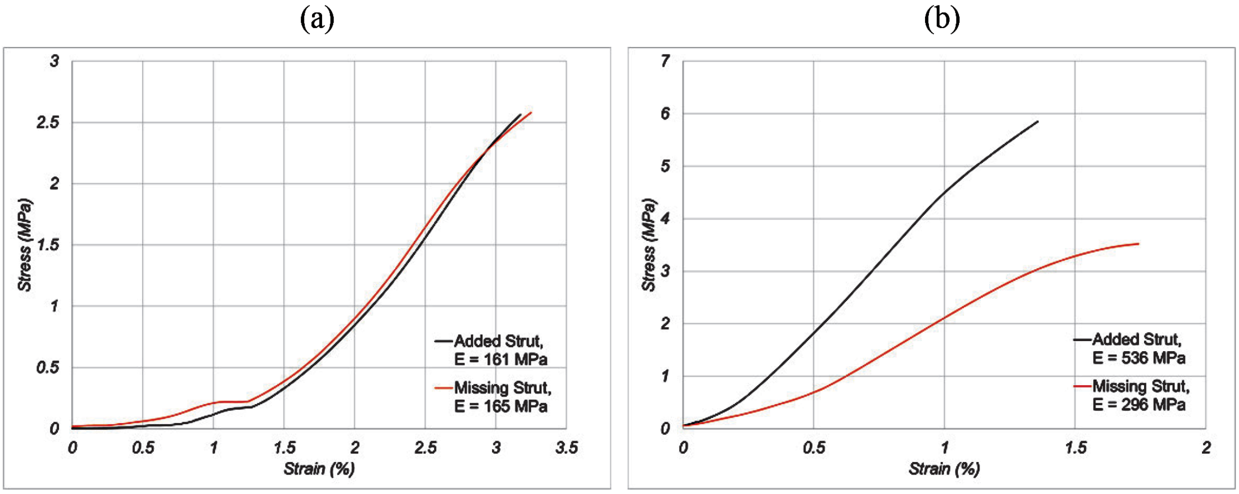

Fig.8 Quasi-static stress-strain curves for the unconstrained auxetic metamaterials (whole area compression); (a) y-axis, (b) z-axis. (Online version in color.)

50% (Fig.8 (b)). This is a significant reduction and should be taken into consideration in any engineering applications involving the use of a structure with a missing central strut.

The effect of the boundary constraint is shown in Fig.9 for compression in the y-axis direction. For these experiments, only the central region of the specimen was compressed. (Whole area compression is not possible due to the presence of the constraining walls.) As shown in the figure, the addition of boundary constraint slightly increases the elastic modulus of the structures. More importantly, however, the modulus values under all conditions of central area compression are significantly higher than in the case of whole area compression. This suggests that the mechanical response of the structures is very dependent on loading configuration.

Finally, the Poisson's ratio values, ν_{yz} (which denote a lateral strain in the z direction as a result of an applied stress in the y direction), were measured for each testing condition. The results are presented in Table1. As can be clearly seen from the Table, the structures exhibit NPR in all cases. Even with the addition of boundary constraint, NPR behavior is maintained, albeit at a slightly reduced level.

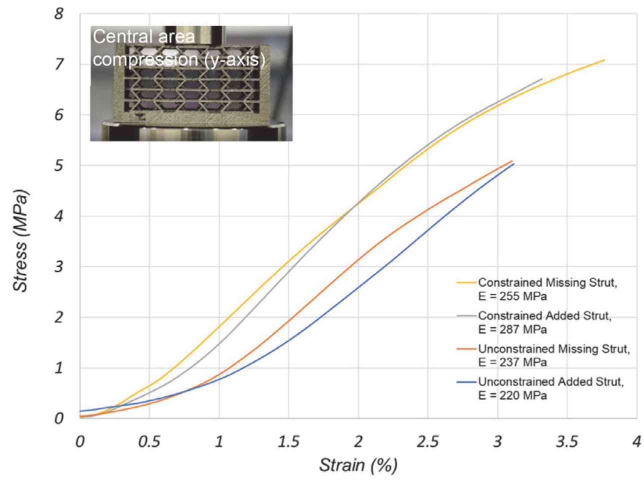

Fig.9 Quasi-static stress-strain curves for the unconstrained and constrained auxetic metamaterials (central area compression in y-axis direction). (Online version in color.)

4 Summary

Additive manufacturing has proven to be an excellent choice for the fabrication of functional lattice structures and metamaterials. The process is very energy and material efficient (green) when compared to more conventional fabrication methods (for example, machining or lost wax casting) and can print complex lattice geometries accurately with few defects and little warping. Post-printing heat treatments can also be employed to relieve residual stresses if necessary. Metallographic examination has shown that the printed material in the lattice struts is dense with very low porosity. However, one of the drawbacks of using additive manufacturing in these applications is the long timescales that are often required to print large structures with complex geometries.

Two examples of metallic 3-D functional lattice structures fabricated via laser printing have been highlighted in this

Table1　Experimentally Measured Poisson's Ratios

Specimen	Poisson's ratio, ν_{yz}
Unconstrained, Central Strut Added	-0.36
Unconstrained, Central Strut Missing	-0.34
Constrained, Central Strut Added	-0.28
Constrained, Central Strut Missing	-0.31

article. The first, a lattice designed to provide low thermal expansion behavior when fabricated from two materials with different CTEs, demonstrated robust mechanical behavior under compression loading. The second type of structure （a re-entrant auxetic metamaterial） was found to exhibit consistent negative Poisson's ratio behavior even when constrained by thick walls.

Continuing improvements and advances in additive manufacturing technology will enable reliable fabrication of future functional lattice structures with increasingly more complex geometries at progressively smaller size scales.

Acknowledgments

The finite element simulations and homogenization studies referred to in this article were performed by Dr. Junyi Lee at Imperial College London. The experimental study of the auxetic metamaterials was performed in collaboration with Dr. Marc Thielen and Professor Thomas Speck at the University of Freiburg, Germany. Appreciation is extended to Dr. Satoshi Emura （NIMS） for assistance with the metallographic sectioning.

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