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Printing and characterisation of Kagome lattice structures by fused deposition modelling

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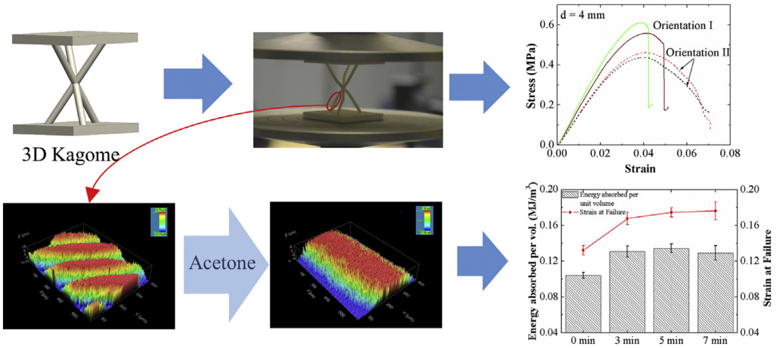
HIGHLIGHTS

- The build orientation affects the compressive properties and failure mode of the Fused Deposition Modeled Kagome unit cells.
- The print imperfections in form of voids and staircase effects contributed to a reduction in the compressive performance.
- Surface treatment with acetone reduced the roughness to optimal levels and resulted in increased compressive properties.

GRAPHICAL ABSTRACT



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ABSTRACT

Sandwich structures with lattice cores exhibit high specific bending strength and stiffness when compared to monolithic structures. Additive manufacturing is able to further expand the available design space to fabricate novel core structures with complex features. In this paper, the compressive performance of the Kagome truss unit cell of acrylonitrile butadiene styrene (ABS) ABS*plus*™ fabricated by fused deposition modelling is investigated. The influences of part build orientation, truss radius and surface roughness on strength and stiffness are critically explored. The change in build orientation improved the average peak strength and effective stiffness by 23% and 19%, respectively. 90% (v/v) acetone was used to polish the printed surfaces and 5 min chemical treatment was optimal based on the measured surface roughness, strength and stiffness values. These single cell studies will help to understand the macroscopic behaviour of the beams and plates with Kagome cores under quasi-static bending and impact loading scenarios.

1. Introduction

Regular lattice and stochastic structures are used extensively in lightweight design, which can be utilised for multi-functional purposes [1]. A wide range of open lattice structures, such as tetrahedral, pyramidal, diamond or octet designs, are being studied for their suitability in sandwich construction. Regular open lattice structures compete with traditionally used honeycomb structures as a core material in sandwich material fabrication.

Additive manufacturing is a disruptive technology that enables fabrication of complex geometric structures with the flexibility of co-printing various materials in layer-wise form from a computer aided design (CAD) model. A range of engineering alloys, polymers, ceramics, and even composite materials can be printed using different types of equipment by employing suitable heat or light sources to the precursor

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in solid, liquid or paste form, which allows solidification to realise the finished component. It is well-known that the geometric core design of the sandwich material has significant influence on its mechanical performance under static, impact and blast loading scenarios. The effective mechanical properties of octet truss structures were investigated through analytical and numerical methods [2]. Rapid prototyping followed by investment casting was used to fabricate tetrahedral cores with face sheets to obtain stiff and strong beams to resist various competing failure modes in a given loading scenario [3]. Optimised tetragonal core structures subjected to bending, crushing and transverse shear with minimum crushing stress constraints were shown to achieve similar weight efficiency when compared to honeycomb structures [4]. Selective laser melting (SLM) was used to fabricate body centred cubic (BCC), body centred cubic with vertical column (BBC-Z), face centred in combination with body centred cubic (F_2BCC) structures [5–8] and tested for their compression response: BCC-Z structures failed in strut buckling whereas BCC structures failed through progressive collapse [6]. The BCC-Z structure showed better compressive performance due to the presence of high load-sharing vertical struts [7]. Tsopanos et al. [9] investigated the influence of process parameters like laser power and exposure time on the compressive properties of BCC structures fabricated by SLM. Insufficient power and exposure time lead to un-melted powder particles resulting in voids and inappropriate fusion resulting in poor mechanical response. Markkula et al. [10] employed fused deposition modelling (FDM) to fabricate three different core topologies namely pyramidal, tetrahedral and strut reinforced tetrahedral (SRT) and tested their compression response. SRT performed better in compression loading with higher yield strength (8.84 times), ultimate strength and higher stiffness (3.44 times) compared to the pyramidal structure. Kadkhodaei and co-workers [11,12] investigated the manufacturability and repeatability of polylactic acid BCC-Z structures and bone scaffolds fabricated by FDM. The compressive bulk properties were used for modelling their uniaxial compressive response, and it was found that only the elastic response predicted by the numerical simulation matched with the experimental measurements.

The Kagome truss structure is a particular type of 3D structure. Kagome means “eyes of a woven basket” in Japanese. The compressive and shear properties of Kagome structures were studied in the past, and it was found that they exhibit better performance than tetrahedral structures. Kagome structures show isotropic behaviour in shear even after yielding [13,14]. The compressive behaviour of wire-woven Kagome structures was studied with the variation of diameter, length, and number of layers: the structure shows better compressive and energy absorption performance than aluminium foam and egg box structures [15]. The compressive and shear performance of Ti-6Al-4V Kagome structures fabricated by SLM was found to be superior to that of conventional honeycomb structures [16]. The stiffness and energy absorption capacity were found to be similar to honeycomb structures [17].

FDM is a widely used additive manufacturing technology for producing functional prototypes. Several investigations on the mechanical properties of FDM fabricated parts have been explored, and it was found that different parameters such as raster orientation, build direction, air gaps, and layer thickness influence the properties of FDM printed parts [18–20]. Li et al. [21] explored the use of FDM to fabricate parts with locally controlled properties and also numerically predicted the mechanical properties. The bonding between the polymer filaments has significant influence on the properties and failure modes of the fabricated parts. Bellehumeur et al. [22] predicted the degree of bonding during the filament deposition process using a heat transfer analysis and found that the extrusion temperature has major influence on the bond formation in FDM processes. Surface roughness is another major issue for additively manufactured components. Especially FDM printed parts are known to have increased surface roughness and to suffer from dimensional inaccuracy [23]. The combination of several factors like build orientation, layer thickness, raster angle, and air gaps has also an effect on the dimensional accuracy and surface roughness of FDM printed parts [24–27]. Generally, surface roughness reduces with a reduction in layer thickness during printing. Also, when parts are built in certain angles rather than in vertical or horizontal direction, the roughness increases due to the staircase effect of added layers. After the fabrication, the surface roughness can be removed by mechanical methods [28–30] as well as chemical methods [31–34]. Kulkarni and Dutta [28] used end mill ball cutter techniques to polish the part for the finer surface finish. Williams and Melton [29] used abrasive flow machining to enhance the surface finish. Pandey et al. [30] used hot cutter machining to remove the staircase for an enhanced surface finish. Galantucci et al. [35] investigated the effect of process parameters like tip size, raster width and slice height on the surface roughness and used diluted dimethyl ketone to polish the ABS leading to improved flexural strength [31]. Garg et al. [32] and Percoco et al. [33] used acetone in vapour and liquid form, respectively, to polish the FDM parts.

This comprehensive study focuses on the compressive performance of Kagome unit cell structures fabricated by FDM as a function of relative density as determined by the cell wall edge radius. The effects of built orientation, strut diameter, and height of the core on the compressive response and polymer fracture behaviour are investigated experimentally. The measured load-displacement responses are simulated using finite element simulations to investigate the deviation of the printed structures from the “as-designed” properties. The constitutive material properties are determined from the tensile dog-bone sample of the cell wall material produced through FDM. The use of chemicals to reduce the surface roughness and duration of the treatment on the compressive response is also explored. This study helps to understand the compressive behaviour of FDM printed Kagome structures and explores the use of chemical treatment on the surface to enhance the properties of FDM printed lattice structures.

2. Experimental details

2.1. Design and fabrication

The 3D Kagome structure is formed by a pair of tetrahedral structures lying vertically inverted with each other and offset by 60° as shown in Fig. 1(a). The unit cell is characterised by the strut diameter (d), height of core (h) and its inclination angle (θ) to the face-sheet. A Stratasys® Dimension Elite FDM machine was used to fabricate the Kagome structures using Acrylonitrile Butadiene Styrene (ABS*plus*™) material. ABS*plus*™ is a 3D printable version of acrylonitrile butadiene styrene (ABS) and commercially supplied by Stratasys. The print-head deposits the ultrafine polymer beads along the extrusion path with a layer build height of 0.1778 mm. In the Catalyst software in the FDM, the solid print model option and surround mode option were selected for model and support material, respectively. Polymethyl methacrylate (PMMA – acrylic) based (P400SR®) support material was used which is soluble in detergent water and can be dissolved at 70 °C following the printing process.

A range of parameters were studied for the Kagome structures, namely the effect of build orientation, diameter variation, and core height. Two samples were studied for each test case. To investigate the effect of build orientation on compressive stiffness, strength and failure modes, two different build orientations for a fixed strut diameter of 4 mm were explored as shown in Fig. 1. The height of the core was maintained at 35 mm, whereas the internal angle was set at 55° to the face-sheet. The average time to fabricate unit Kagome cells with two face sheets in orientation I and orientation II is 314 and 281 min, respectively. Though printing in the orientation I requires longer time, it only needs about half the amount of support material required for printing the unit cell in orientation II. In order to establish the effect of diameter variation on the compression response of Kagome cells, struts were designed with 2.0, 2.4, 3.0, and 4.0 mm diameters and printed in orientation I with the same height of 35 mm. To study the effect of core