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Compressive failure modes and energy absorption in additively manufactured double gyroid lattices

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ABSTRACT

Lattice structures are excellent candidates for lightweight, energy absorbing applications such as personal protective equipment. In this paper we explore several important aspects of lattice design and production by metal additive manufacturing, including the choice of cell size and the application of a post-manufacture heat treatment. Key results include the characterisation of several failure modes in double gyroid lattices made of Al-Si10-Mg, the elimination of brittle fracture and low-strain failure by the application of a heat treatment, and the calculation of specific energy absorption under compressive deformation (16×10^6 J m^{-3} up to 50% strain). These results demonstrate the suitability of double gyroid lattices for energy absorbing applications, and will enable the design and manufacture of more efficient lightweight parts in the future.

1. Introduction

Additive manufacturing (AM) describes a range of processes that fabricate components directly from CAD representations in a sequence of bonded or integrated layers. AM components need not be constrained by the same design restrictions that apply to conventional manufacturing (e.g. subtraction or forming); they may be freeform and quite complex, providing the opportunity for lightweighting and increased functionality.

One way in which AM component redesign may be achieved is by the replacement of otherwise solid volumes with lightweight cellular structures, or lattices [1–7]. In terms of specific mechanical properties, latticed components may actually be sub-optimum compared to those stemming from topology optimisation (TO) approaches, but they may offer superior performance in cases which feature uncertainty in the loading conditions. Also, because they generally do not require the large computational resources associated with iterative TO, they are easier to implement in CAD models. A further benefit provided by lattice structures, one which is examined in this work, is their ability to absorb large amounts of deformation energy in a predictable manner, which is of great importance in the design of packaging materials and personal protective equipment (PPE) such as armour.

There are several variables in lattice structure design that affect their mechanical properties and deformation behaviour. The feature that has received most attention to date is the relative density, or volume fraction, of the lattice; see, for instance, the studies of Yan et al. [8,9] and Gümrük et al. [10]. This is unsurprising, since the relationships between volume fraction and the usual properties of interest, such as the modulus and strength of the lattice, are well established and have been verified for another, closely related, structure type; foams [11–13]. Other lattice design variables include the size and geometry of the tessellating unit cell. Only a handful of lattice cell types have been manufactured by AM and mechanically tested so far, most coming from the family of strut-based cells, such as the body-centred-cubic (BCC), the face-centred-cubic (FCC) and several reinforced versions of these [5,10,14–16].

There exists another family of geometries which have great potential as AM lattices; the triply periodic minimal surfaces (TPMS). Of these, only the Shoen gyroid has been examined in detail; experimentally by Yan et al. [3,8,9,17] and theoretically by Khaderi et al. [18]. One form of the gyroid lattice known as the double gyroid (DG) was recently identified as having high stiffness and low maximum von Mises stress compared to a variety of other cell types [19], making it particularly suitable for use in lightweight components. Furthermore, Aremu et al. [19] noted that the DG lattice, unlike several other lattice types, possesses axisymmetric stiffness, again making it a good candidate for applications where the exact nature and direction of the loads are not fully known or if they are subject to large uncertainties. The theoretical study by

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Kapfer et al. [20] indicated that the DG lattice possessed superior mechanical properties compared to its network phase equivalent. In a novel demonstration of the DG structure's suitability for AM, Qin et al. [21] recently examined 3D graphene assemblies based on the DG architecture, deriving scaling laws for their mechanical performance. More information regarding the gyroid geometry and naming scheme is provided in Section 2.1.

Al-Si10-Mg belongs to a family of high strength aluminium alloys known for their good castability, corrosion resistance and ability to be strengthened by artificial ageing [22]. These alloys are used throughout the aerospace and automotive sectors, where the weights of all components, even the smallest and lightest, are scrutinised as they cumulatively affect the performance of the vehicle in which they reside, as well as the associated running costs and greenhouse gas emissions. Al-Si10-Mg is therefore a good material for investigations with AM lattices, as the demand for lightweight components in high strength alloys is already established. A post-manufacture heat treatment was applied to the lattice structures because it was previously observed to significantly alter the microstructure and mechanical properties of selectively laser melted Al-Si10-Mg [23,24], enhancing its ductility at the expense of reduced strength. Another relevant result comes from Maskery et al. [25], who applied the same heat treatment to strut-based Al-Si10-Mg lattice structures, finding that it improved their ability to absorb energy under compressive deformation compared to as-built structures.

In this paper, we address the relationship between structural performance and cell size in AM lattices, which to date has received little attention but is an important factor in AM lattice design. We go on to investigate the effect of an easily implementable heat treatment on lattice deformation, before quantifying and comparing the energy absorption of heat treated and as-built specimens. Following this introduction, the details of lattice design, production, testing and heat treatment are given, followed by the experimental results and discussion. Conclusions are provided in the final section.

2. Experimental details

2.1. Gyroid lattice design

The gyroid belongs to the family of triply periodic minimal surfaces (TPMS), a subset of the larger class of constant mean curvature (CMC) surfaces. In particular, TPMS are categorised by their zero mean curvature at every point.

TPMS equations describe 3D surfaces which, for the purpose of AM, can be taken as the boundary between void and solid material. Matrix phase gyroid structures with arbitrary numbers of cells and volume fractions can be generated by finding the $U=0$ isosurface of the equation

$$U = (\cos(k_x x)\sin(k_y y) + \cos(k_y y)\sin(k_z z) + \cos(k_z z)\sin(k_x x))^2 - t^2, \quad (1)$$

where k_i are the TPMS function periodicities, defined by

$$k_i = 2\pi\frac{n_i}{L_i} \text{ (with } \quad i = x, y, z), \quad (2)$$

n_i are the numbers of cell repetitions in x, y and z, and L_i are the absolute sizes of the structure in those dimensions.

Matrix phase lattices comprise a wall of solid material bounded by two unconnected void regions. These are distinct from network phase structures, which contain only one solid and one void region. This is illustrated in Fig. 1. In this paper, we will adopt the convention of referring to the matrix phase gyroid lattice as the double gyroid (DG).

In Eq. (1), t effectively controls the thickness of the cell walls, and thus also the volume fraction, ρ^*, of the resulting lattice structure. The relationship between t and ρ^* is unique for each TPMS cell type. For the DG lattice, we found this can be approximated reasonably well (in the range $0.1 \leq \rho^* \leq 0.9$) with the linear equation $\rho^* = 0.675t - 0.012$, though, to ensure the DG lattices in this paper possessed exactly the desired volume fraction, we employed a higher order polynomial form of $\rho^*(t)$.

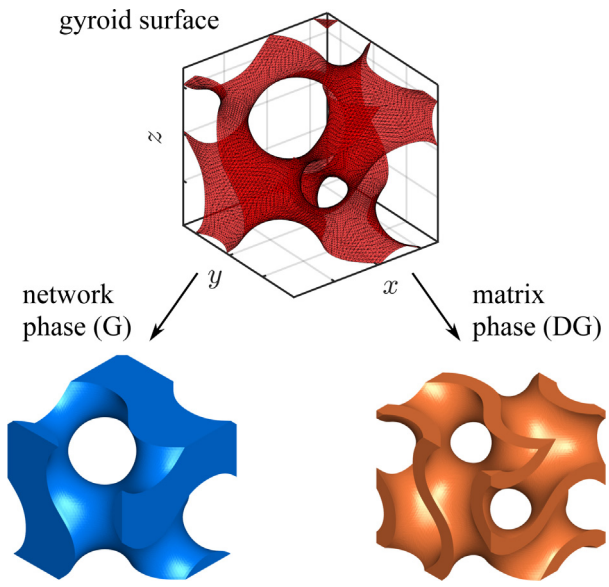

Fig. 1. The TPMS gyroid surface (above) provides the network and matrix phase cells for AM (below).

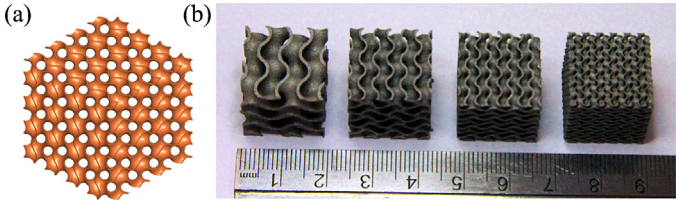

Fig. 2. CAD representation of the DG lattice (a) and photographs of SLM manufactured specimens (b). The specimens in (b), from left to right, contain cells of size 9, 6, 4.5 and 3 mm.

2.2. Selective laser melting of double gyroid lattice specimens

Double gyroid lattice specimens composed of Al-Si10-Mg were fabricated using a Renishaw AM250 selective laser melting (SLM) machine. The laser power was 200 W and a meandering scan pattern with 130 μm hatch spacing was used. The laser point distance and exposure time were 80 μm and 140 μs, respectively. The Al-Si10-Mg powder was deposited in 25 μm layers prior to each laser scan and the build platform was held at 180 °C during specimen production. Photographs of manufactured DG lattice structures are provided in Fig. 2, alongside a CAD representation. The range of DG lattice unit cell sizes was 3, 4.5, 6 and 9 mm, which were chosen to provide integer periodicities in the 18 mm specimens. These specifications, along with the total number of lattice cells and the wall thickness for each specimen, are provided in Table 1. The volume fraction in each case was 0.22, which was obtained using $t = 0.3409$ in Eq. (1).

2.3. SLM material and lattice characterisation

Uniaxial compression testing of the DG lattice specimens was conducted using an Instron 5969 universal testing machine with a 50 kN load cell. The loading direction was equivalent to the SLM building direction. The compressive deformation rate was