Acta Materialia 116 (2016) 14–28

Contents lists available at ScienceDirect

Acta Materialia

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

Full length article

Additively-manufactured metallic micro-lattice materials for high specific energy absorption under static and dynamic loading

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A R T I C L E I N F O

Article history:
Received 17 May 2016
Accepted 30 May 2016

Keywords:
Octet truss lattice
Specific energy absorption
Additive manufacturing
Split Hopkinson bar testing
Finite element analysis

A B S T R A C T

An octet truss lattice material is designed for energy absorption purposes featuring an exceptionally high specific energy absorption, a constant plateau stress between initial yield and densification, and zero plastic Poisson's ratio. It is demonstrated through detailed finite element simulations that the meso-structural response of metallic lattice materials under compression changes from an unstable twist mode to a stable buckling free mode at a relative density of about 0.3. Furthermore, it is found that the nature of the macroscopic stress-strain curve changes from mildly-oscillating to monotonically-increasing as the meso-structural deformation mode changes, while a stress-plateau is observed at relative densities above 0.3. Since the specific energy absorption is a monotonically increasing function of the relative density, lattice materials of relative densities around 0.3 feature both a plateau stress and a high specific energy absorption capability. Prototype materials are built from stainless steel 316L using Selective Laser Melting. The basic building element of the micro-lattices are 2.2 mm long beams with a 500 μm diameter cross-sections. Detailed micro- and meso-structural analysis including tomography, microscopy and EBSD analysis revealed substantial local material property variations within the lattice structure. Compression experiments are performed under static and dynamic loading conditions confirming the anticipated exceptional energy absorption material characteristics for strain rates of up to 1000/s.

1. Introduction

Truss lattice materials are man-made open porous cellular solids with periodic truss microstructures. In essence, these are space-filling 3D networks made from hollow or solid truss elements. Depending on their nodal connectivity, the mechanical response of highly porous truss lattice materials may be described as either bending-dominated or stretching-dominated [1]. With recent progress in micro- and nano-fabrication technology, lattice materials can now be made with truss diameters ranging from the submicron to the millimeter level (e.g. Ref. [2]). Direct laser writing and additive manufacturing techniques provide an excellent control over the lattice geometry, thereby enabling the fabrication of almost any open porous truss architecture. At the same time, important scale effects in the parent material may be leveraged by reducing the characteristic structural dimensions. For example [3], built copper micro lattices with truss diameters of a few microns only that were stronger than fully-dense pure copper. [4] reported a size-effect in the stiffness and strength of alumina when coating a polymer lattice template. [5] demonstrated that hollow Al_2O_3 and Ni-P micro lattices provide a nearly constant stiffness per unit mass density over three orders of magnitude of density. Even at effective densities of only a few mg/cm^3, the Young's modulus to density ratio of microlattice materials is still close that of fully-dense metals.

The octet truss lattice architecture plays a central role in the above works as it is a statically-determinate space-filling Platonian solid which exhibits stretching-dominated meso-structural response. Even though the mechanical properties of the parent material may be size dependent, results regarding the deformation response of the octet truss lattice are applicable to lattice structures at the micron, millimeter and centimeter scale. Building on the early work of [6], [7] derived analytical estimates of the basic macroscopic mechanical properties of the octet truss lattice material. A multi-surface plasticity model for ideal octet truss lattice

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http://dx.doi.org/10.1016/j.actamat.2016.05.054
1359-6454/

materials has been derived by Mohr [8]; while a general computational homogenization approach for describing the non-linear constitutive response of lattice materials has been presented by Vigliotti et al. [9]. Messner et al. [10] made use of Bloch wave theory and detailed finite element calculations to derive a continuum model representing long-wavelength wave propagation in truss lattice materials.

Wadley and co-workers developed innovative manufacturing processes to make lattice materials from wire grids and sheet material (e.g. Refs. [11–13]). Knowing that the truss waviness knocks down both the stiffness and strength (e.g. Ref. [14]), special attention was paid to manufacturing lattice structures with minimal initial truss curvature. Many recent studies now rely on additive manufacturing for making metallic truss lattice materials. [15] produced stainless steel 316L Body-Centered-Cubic (BCC) lattice specimens with strut diameters of 210 μm and relative densities ranging from 4% to 14%. They report a significant loss in the basis material stiffness and strength related to defects introduced through Selective Laser Melting (SLM). Furthermore, their results confirm that the compressive response of BCC lattices is bending dominated, as expected from their detailed finite element simulations. In a second study on SLM made 316L lattices [16], they found that the manufacturing related lattice defects has a particularly harmful effect on the material properties under shear loading. Drop tower impact experiments on sandwich panels by Mines et al. [17] revealed that SLM made Ti-6Al-4V BCC lattices can match the performance of aluminum honeycombs. The analysis of dynamic compression experiments at a nominal strain rate of about 1000/s on tetrahedral aluminum truss core structures with 13.4 mm long and 1.5 mm thick struts suggests that strut buckling is delayed due to inertia effects [18].

Selective laser melting of a Ti-rich TiNi shape memory alloy has been employed by Li et al. [19] to create an auxetic lattice material. Their results clearly demonstrate the important effects of the SLM process parameters on the resulting parent material structure. Electron beam melting (EBM) provides an alternative to SLM with potentially higher production speeds, but the surface quality provides only little immediate improvements over that obtained through SLM [20], [21] created Ti-6Al-4V cubic and diamond lattice structures of relative densities of up to 17% using EBM. Their static and dynamic compression experiments show progressive crushing from the specimen boundary under static loading conditions and random cell layer collapse of the re-entrant cube lattice under dynamic loading.

From a strength perspective, lattice structures with hollow trusses (e.g. Ref. [22]) provide a higher load carrying capacity per unit density due to the higher second moment of inertia in comparison to solid round cross-sections. Design maps for octet truss architectures with struts of non-circular cross-sections have been developed by Elsayed and Pasini [23] to ensure that elastic buckling and plastic yielding occur simultaneously. The potential of hollow micro-lattices for energy absorbing systems is reemphasized by Evans et al. [24]. They show that the specific energy absorption of hollow truss lattices is even higher than that of honeycombs for the same relative density and basis material.

The space of potentially interesting truss lattice geometries is vast. Among other aspects, the design of a truss lattice material involves (a) the choice of the basis material, (b) the choice of the lattice geometry, e.g. cubic, tetrahedral, octet, etc., (c) the choice of the strut shape, and (d) the choice of the relative density of the lattice material. Here, an attempt will be made to keep the unit cell size of the truss material as small as possible to generate a lattice material, which can be treated as a homogeneous solid in standard engineering applications (e.g. energy absorption structures for transportation vehicles, jet engine components, etc.). By limiting our attention to additive manufacturing with metals, this design objective led us to 316L stainless steel as basis material. As compared to other powder materials such as aluminum or titanium alloys, struts of only 500 μm diameter can be manufactured from stainless steel while maintaining reasonable geometric accuracy.

Among different lattice geometries, we chose the octet truss lattice configuration as it provides a nearly isotropic elastic response. It features a unit cell composed of two Platonic solids: the tetrahedron and the octahedron (Fig. 1a). By definition of a Platonic solid, all struts have the same shape and length L. Its configuration resembles to a Face-Centered Cubic (FCC) crystal when the struts are considered as the shortest distance of atom-to-atom interaction. The surrounding light green cube in Fig. 1a represents the macroscopic volume filled by the octet lattice unit cell. The remaining open design questions, the choice of strut shape and relative density, will be determined through a parametric finite element study. The main criterion for selecting the “optimal” configuration will be the material's energy absorption characteristics: (1) constant stress plateau and zero plastic Poisson's ratio to allow for a constant deceleration of an impacting rigid mass, and (2) high specific energy absorption, i.e. the plastic work performed in the plateau regime under uniaxial compression shall be maximized for a given effective material density.

In the present work, we firstly carry out a parametric finite element study to identify the optimal relative density for which the compressive response of a stainless steel 316L octet truss lattice material achieves the above design objective. In particular, we determine the effect of the relative density and truss cross-section variations on the macroscopic stress-strain response for uniaxial compression. Subsequently, truss lattice specimens of a relative density of about 30% are manufactured and subjected to compression under static and dynamic loading conditions. In addition, the stainless steel 316L basis material is characterized under compression for strain rates of up to 1000/s. It is demonstrated both numerically and experimentally that an octet truss lattice material of a relative density of 30% is free from any initial peak stress and exhibits the ideal engineering stress plateau of an energy absorption material prior to densification. Furthermore, it is shown that the specific energy absorption of the tested material is significantly higher than that of conventional hexagonal honeycomb.

2. Analytical preliminaries

2.1. Relative density

The relative density $\bar{\rho}$ is defined by the ratio of the macroscopic

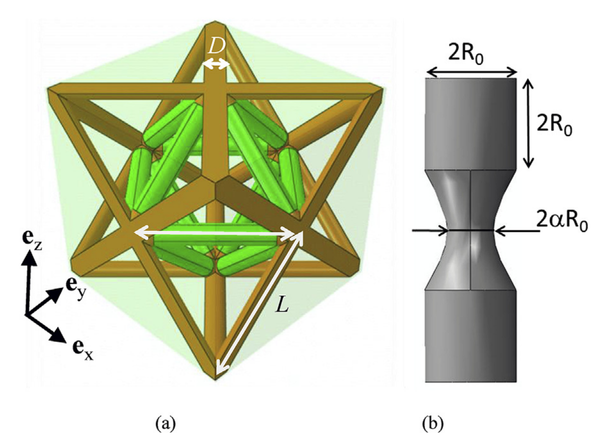

Fig. 1. (a) Unit cell of the octet truss lattice material, (b) geometry of a single strut.