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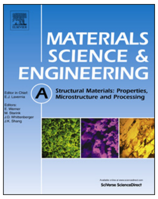

Deformation behaviour of stainless steel microlattice structures by selective laser melting

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ABSTRACT

Recent developments in selective laser melting (SLM) have enabled the fabrication of microlattice structures with periodic unit cells: a potential sandwich core material for energy dissipation. In this study, a full scale 3D finite element (FE) model was developed to investigate the macroscopic deformation of microlattice structures and the microscopic stress and strain evolution in the solid struts of the microlattice. The constitutive behaviour of SLM stainless steel 316L, the parent material of microlattice, was accurately characterised using non-contacting imaging techniques and input to the developed FE model, which was then validated by uniaxial compression experiments. It was found that local plastic stress and strain evolve near the nodal joint, thus forming a plastic hinge, whilst the majority of the strut remains elastic. The localised plastic stress/strain and the volume of plastic zone increase with the compression of the microlattice, resulting in the nearly plateau region with slight linear hardening in the stress–strain curve. The final densification process is dominated by the self-contact interaction among struts in the microlattice. Finally, the FE predictions reveal that the deformation of a microlattice is significantly affected by applied boundary conditions and constitutive properties of SLM parent materials such as Young's modulus.

1. Introduction

Cellular materials have been increasingly used in transport applications due to their high strength-to-weight ratio and excellent energy dissipation capacity [1–5]. Lattice structures, which offer better tailorability of properties owing to the periodic nature of unit cells, are the choice of core materials for sandwich structures to dissipate energy [6–13]. The application to energy dissipation requires a better understanding of both macroscopic deformation of the lattice core and the microscopic stress and strain evolution in the solid struts.

A number of experimental, numerical and analytical studies [6,7,9–12,14–16] have been reported on the mechanical behaviour, such as deformation processes of cellular materials with periodic unit cells. The mechanical response is not only determined by the relative density and properties of the parent solid materials but also by the geometry/topology (or the architecture) of the unit cells. This topology can significantly influence the overall stiffness, strength and energy dissipation capacity of a lattice structure. For instance, it was found that adding struts, which are parallel to the loading direction, to a body centred cubic (BCC) microlattice changes the deformation and failure mode, and increases the stiffness and strength [11,12,16]. In a sandwich structure, the specific mechanical properties of the lattice (or truss) core are significantly higher than those of a metallic foam core [6,9]. Various analytical beam models as well as 3D finite element (FE) solid models have been established to further explore the deformation process of lattice structures and to facilitate the optimisation of cellular geometry and topology [12,16,17]. However, most of the models only simulated the deformation of a unit cell, and the effect of boundary conditions may be underestimated when the behaviour of unit cells is extended to the bulk lattice [11]. Moreover, the local stress and strain in struts of a lattice need to be fully examined and linked to the overall behaviour of the lattice.

Lattice structures have been conventionally manufactured using various techniques such as investment casting, deformation forming and metal textile approaches [7,9,15,18]. Recent developments in additive manufacturing, especially selective laser melting (SLM), have advanced the fabrication of metallic microlattice structures (strut diameter down to a few hundred micrometres) with more complex topological geometry of unit cells [11,16]. The SLM processing parameters, such as laser power and scan speed (or laser exposure time), considerably affect internal microstructure and defects in the material and therefore its mechanical properties [19,20]. Tsopanos et al. [13] investigated the influence

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of processing parameters on uniaxial compressive behaviour of stainless steel microlattice structures, and revealed that the higher laser powers can result in nearly fully dense struts and strength comparable to that in the bulk steel. Only few studies available in the literature [11,13,17] quantified the stress–strain curve of SLM struts under uniaxial tensile loads. However, to facilitate FE modelling, the constitutive response of struts should be more accurately characterised, e.g., using the non-contacting extensometer by laser or photography.

The aim of the study reported here was to investigate the deformation process and localised stress/strain evolution of microlattice structures produced by SLM techniques. Uniaxial tension experiments supported by high resolution imaging were conducted to measure the constitutive properties of SLM stainless steel 316L struts, including Young's modulus, yield stress, hardening behaviour and failure mode. A full scale 3D FE model was then developed to predict the deformation of microlattice structures subjected to compressive loading, and was validated by the uniaxial compression experiments. The evolution of localised stress and strain in struts was analysed to be related to the overall deformation of the microlattice. The FE model was rerun as a function of boundary conditions and parent material properties to explore their effects on the deformation of microlattices.

2. Experimental procedure

2.1. Materials and microstructure

The selective laser melting (SLM) technique was used to manufacture stainless steel 316L microlattice structures in which $4 \times 4 \times 4$ body centred cubic unit cells were repeatedly stacked in three orthogonal directions (Fig. 1(a)). Each BCC unit cell with an edge length of ~2.7 mm, consisted of eight struts of ~220 μm diameter. The density of the microlattice was ~226 kg m^{-3}. To investigate the constitutive behaviour of the parent material in microlattice structures, individual 316L struts of ~220 μm diameter and 50 mm length were also produced in the SLM facility using the same processing parameters as those for microlattices.

As shown in Fig. 1(b), the stainless stain powders were completely fused together within the melted and solidified zone, giving rise to the curved edges in the cross-section. A fine cellular and dendritic microstructure formed in the SLM 316L steel as a result of the rapid solidification nature. Porosity also occurred, especially near the edge of solidified zones; smaller pores may be observed within some zones (not shown in the figure).

2.2. Mechanical tests

Uniaxial tension experiments were conducted on the individual struts to determine the stress–strain curves at quasi-static rates (7×10^{-5} s^{-1}) in an INSTRON (INSTRON, MA, USA) mechanical testing machine with a 50 N load cell. An in-house gripping device with a universal joint was designed to clamp the strut specimen in order to minimise the slippage and misalignment effects during the tension tests (Fig. 2(a)). The deformation of the individual struts was recorded in a JAI (JAI Ltd., Japan) BM-500 GE high resolution camera at a resolution of ~12.5 μm per pixel to accurately quantify the strain in the specimens.

The microlattice structures were bonded to two steel platens with epoxy resins and then subjected to uniaxial compressive loading in the INSTRON machine with a 500 N load cell to characterise the behaviour at quasi-static rates (~0.001 s^{-1}). The end surfaces of the structure were thus restricted from sliding in the platens. The real-time compressive deformation process was captured using the same JAI imaging system.

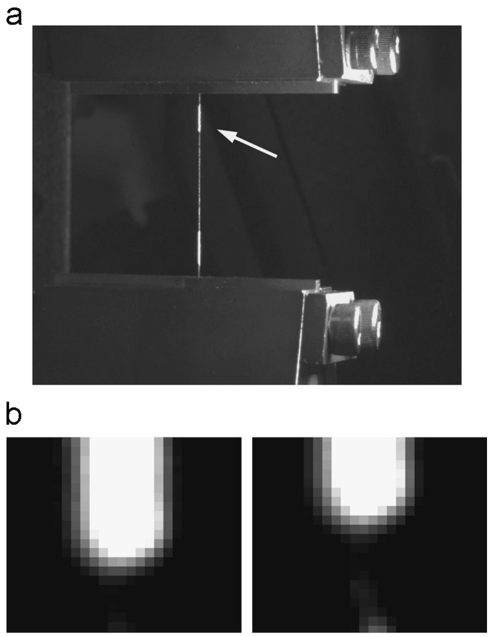

Fig. 2. (a) A uniaxial tension experiment on a single SLM strut marked with two white stripes and clamped in an in-house fixture fitted in an INSTRON machine, and (b) two photographs showing the local pixels at two different displacement stages near the top white stripe edge as indicated by the arrow in (a).

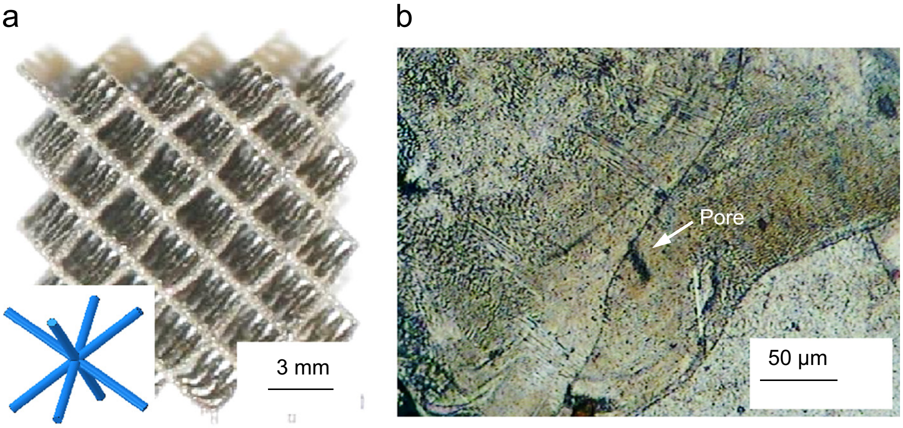

Fig. 1. (a) A stainless steel 316L microlattice structure with BCC unit cells manufactured by SLM, and (b) cellular and dendritic microstructure in parent material of the struts observed in the optical microscope.