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Mapping local deformation behavior in single cell metal lattice structures

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ABSTRACT

The deformation behavior of metal lattice structures is extremely complex and challenging to predict, especially since strain is not uniformly distributed throughout the structure. Understanding and predicting the failure behavior for these types of light-weighting structures is of great interest due to the excellent scaling of stiffness- and strength-to weight ratios they display. Therefore, there is a need to perform simplified experiments that probe unit cell mechanisms. This study reports on high resolution mapping of the heterogeneous structural response of single unit cells to the macro-scale loading condition. Two types of structures, known to show different stress-strain responses, were evaluated using synchrotron radiation micro-tomography while performing in-situ uniaxial compression tests to capture the local micro-strain deformation. These structures included the octet-truss, a stretch-dominated lattice, and the rhombic-dodecahedron, a bend-dominated lattice. The tomographic analysis showed that the stretch- and bend-dominated lattices exhibit different failure mechanisms and that the defects built into the structure cause a heterogeneous localized deformation response. Also shown here is a change in failure mode for stretch-dominated lattices, where there appears to be a transition from buckling to plastic yielding for samples with a relative density between 10 and 20%. The experimental results were also used to inform computational studies designed to predict the mesoscale deformation behavior of lattice structures. Here an equivalent continuum model and a finite element model were used to predict both local strain fields and mechanical behavior of lattices with different topologies.

1. Introduction

Light-weighting metal lattice structures are being studied extensively due to their load bearing properties and low density [1–5], especially in the biomedical [6–8] and aerospace [9] industries where the tradeoff between strength and weight is very important [10,11]. With the advent of additive manufacturing (AM) methods, such as Selective Laser Melting (SLM™), a range of lattice structures can now be efficiently fabricated at various length scales not previously attainable. SLM is a powder bed process where a laser beam is raster-scanned across a bed of metal powder particles in a specified pattern, layer by layer, to create a 3-dimensional (3D) part. Metal AM methods have opened the design space immensely for building low-density structures with high strength, however these methods can result in structures that vary significantly from the idealized design. Specifically, the powder bed process is known to introduce unwanted defects into a metal structure, such as "parasitic" material, porosity, and surface distortion. Some processing related defects are due to issues such as lack of fusion and gas porosity, which are difficult to control and can yield parts with a variety of densities and void distributions [12].

Understanding and predicting the mechanical behavior of lattice structures fabricated in such a manner is therefore important as the intended applications are reliant on the structural integrity of such parts. Many recent studies have focused on such investigations [6,10,13–21], highlighting the role of many factors, such as the microstructure of the metal, defects introduced during the build process, and lattice topology. Attention in particular has focused on the scaling relationship between apparent elastic stiffness and relative density, which is sensitive to the lattice topology [22]. In addition, Mazur et al. [18] and others [16,23] have shown

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that failure modes and the transition from linear elastic and non-linear anelastic response varies based on whether the lattice is stretch- or bend-dominated and the relative density of the lattice. Lattice topology thus dictates the stress-strain response; for example, lattice structures with a stretch-dominated topology have exceptional stiffness and strength for a given relative density, while lattice structures with a bend-dominated topology and same relative density show more compliance, and are known to absorb energy well [22]. Also, while stretch-dominated lattices display significant softening after the onset of anelasticity, bend-dominated lattices exhibit a plateau stress similar in magnitude to the initial peak stress.

Along with topology, the microstructure of the selected AM material is an important factor in the mechanical performance. A wide range of possible metals and alloys can be selected and, in turn, the microstructure of each type of metal can be manipulated by applying various heat treatments. Often AM metals, like Ti-6Al-4V (Ti64), are heat treated in order to increase ductility [20,24–26]. Along with microstructure, fabrication defects can, depending on the severity and defect distribution, play a significant role in affecting the mechanical response. Tomography, a 3D non-destructive imaging technique used to glean structural information with micrometer resolution over a several mm field of view [27,28], has played an invaluable role in this regard. Also, in-situ tomography has been used to investigate both defects and failure mechanisms in metals [12,29–32] by tracking the damage evolution and defect distribution, elegantly showing how large defects can alter the failure mechanisms. Several studies have used tensile testing during X-ray tomography to map void growth in heterogeneous ductile materials, such as dual phase steels [31] and Ti6Al4V [32]. At the Advanced Light Source's (ALS, LBNL, Berkeley, CA) tomography beamline (8.3.2) there is a dedicated custom built mechanical testing device developed by Haboub et al. [33] and Bale et al. [34] that can test structures in both compression or tension. The high flux achieved at synchrotron facilities enables in-situ mechanical testing to take place over only a few hours, while lab based tomography systems would take a prohibitively long time to acquire the necessary timesteps required during loading.

Although there has been significant attention placed on evaluating the stress-strain or force-displacement response of lattices with different material properties, defects, and topologies, most of these studies fall short in understanding the local deformation response. This is a significant void in our understanding, as the derived macroscopic response may not really represent a material point anywhere in the structure considering the stress is not uniformly distributed. To this end, in this study we investigate in situ – using high resolution synchrotron radiation micro-tomography (SRμT) – the compression response of unit cell lattice structures with two different topologies: octet-truss (OT), which is stretch-dominated, and rhombic dodecahedron (RD), which is bend-dominated. The SRμT provides real time 3D images with micrometer resolution and the tomography data is used to evaluate failure mechanisms, to identify defects in the SLM structure, and to track the local strain during different amounts of imposed loading. These results are then compared to computational models, finite element and equivalent continuum, developed to predict the elastic and failure behavior of these types of light-weighting structures.

2. Experimental procedures

2.1. Fabrication of lattice structures

A total of six different types of Ti64 alloy structures (two different topologies and three different relative densities) were built using a powder bed system (Concept Laser M2) at Proto Labs (Raleigh, NC).[1] The sample test matrix is shown in Table 1. Before being removed from the build plate, all samples were heat-treated at 900 °C for 1 h using a vacuum furnace at a heating rate of 10 °C/min. After heat-treatment the samples were gas cooled down to room temperature. There were two sets of SLM Ti64 lattice samples built at different times, which were heat-treated in different furnaces. It should be noted that these two batches of samples displayed different mechanical properties; this could be due to the subsequent build and processing differences. The material model used here was tuned to results from the OT 10% relative density unit cell (from the second batch of samples) and then used for all other cases within that sample group. It is important that the model is tuned to the correct sample group since consequently if the mechanical properties of the material being tested are inaccurate then the entire model predictions will be incorrect.

The connectivity of the struts and the shape of the unit cell define the lattice topology. The unit cell dimensions for the two different lattice topologies, OT and RD, were selected in order to reach a target relative density using sub-millimeter strut diameters. The selected relative densities were 10, 20, and 30%, where the relative density is defined by the ratio of the macroscopic density of the cellular structure to the density of the structure's material:

$$\bar{\rho} = \frac{\rho}{\rho_S}$$

Each topology's relative density is defined below by the following approximate analytical relationships:

$$\bar{\rho}_{OT}(a,l) = 6\sqrt{2}\pi\left(\frac{a}{l}\right)^2$$

$$\bar{\rho}_{RD}(a,l) = \frac{3}{2}\sqrt{3}\pi\left(\frac{a}{l}\right)^2$$

Where a and l are the radius and length of a strut, respectively [17].

2.2. Compression testing and tomography

The in-situ compression tests were performed on unit cell lattices in a custom built testing fixture designed to fit within the tomography hutch and allow for 180° rotation. The tomographic imaging was performed at Beamline 8.3.2 at the Advanced Light Source (Lawrence Berkeley National Laboratory, Berkeley, CA, USA). The experimental setup was similar to standard tomographic procedures [35] where the sample and testing rig were rotated in an X-ray beam and the transmitted radiographic projections were imaged via a scintillator, magnifying lens, and a digital camera. For this experiment the effective voxel size was 3.3 μm. The samples were mainly imaged in polychromatic or ‘white’ light mode, where the entire available energy spectrum is used. This mode is useful when scanning high-density metals. Reconstructed images were obtained via a filtered back-projection algorithm using the software package Octopus [36]. Three-dimensional visualization, segmentation, and quantification was performed using Avizo™ software [37].

During compression testing each lattice structure was loaded using displacement control at a nominal quasi-static strain rate of 10^{-3} s^{-1}. During testing the lattice was held at specified displacements along the force-displacement curve to allow for the entire tomography scan to complete, with each scan taking ~5 min. There was some relaxation observed during each scan.

[1] https://www.protolabs.com/.