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Mechanical properties and deformation behavior of additively manufactured lattice structures of stainless steel

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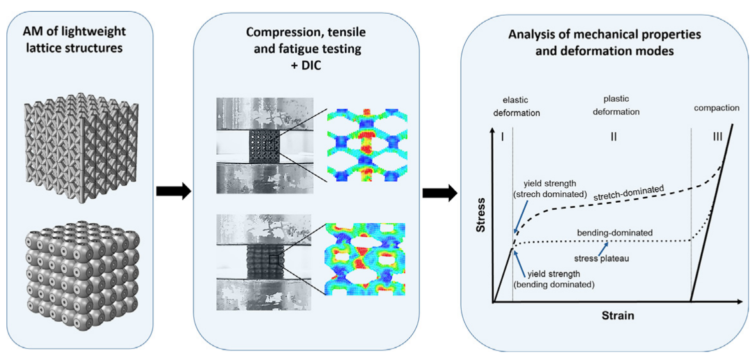
HIGHLIGHTS

- Two steel lattice structures, f2cc,z and hollow spherical, were additively manufactured and mechanically characterized.
- The f2cc,z lattice revealed a stretch dominated, whereas the hollow spherical lattice a bending dominated deformation mode.
- Specific energy absorption of f2cc,z was higher than for the hollow spherical specimens and comparable with bulk material.
- High strain concentration at nodes of lattice structures mainly caused failure in these regions.
- Under cyclic loading, lattice structures have a lower endurance limit than bulk material.

GRAPHICAL ABSTRACT



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ABSTRACT

In this work, we used the powder bed fusion selective laser melting (SLM) technique to build two different lattice structures, i.e. of type f2cc,z and hollow spherical, to investigate their plastic deformation behavior during tension, compression and cyclic testing. The stainless steel AISI 316L/1.4404 was used as model alloy for lattice structures that exhibited a relative density of 33% compared to bulk samples and a part density of 2.623 g/cm^3. Using optical microscopy, SEM, EDS, DIC analyses as well as tension, compression and fatigue testing, microstructures and mechanical properties of the two types of lattice structures were compared with annealed counterparts, SLM-produced bulk and reference specimens of the same chemical composition. It was found that the f2cc,z lattice structures deformed by stretch, whereas the hollow spherical lattice structures presented a bending dominated deformation mode. Consequently, f2cc,z lattice specimens revealed higher energy absorption capacity and were capable of bearing higher loads. In addition, the f2cc,z samples showed comparable specific energy absorption with respect to bulk reference samples. The plastic deformation behavior of the different lattice structures has been assessed by considering geometrical and microstructural aspects. Implications on usability and potential improvements were also discussed.

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1. Introduction

Additive manufacturing (AM) has gained significant scientific and industrial importance during the last 30 years [1,2]. With a compound annual growth rate of approximately 30% between 2010 and 2015, AM industry reached a value of USD 5.1 billion in 2015 [3]. The high growth rates are related to an increasing interest of the industrial manufacturing community in AM as a standard production method [4]. The technology enables the production of fully dense bulk volumes in a layer-wise fashion by melting a powder or wire feedstock with a high-energy source (laser or electron beam), as opposed to conventional subtractive or formative techniques [1,5]. Currently, most relevant metal AM technologies can be divided into powder bed fusion techniques, e.g. selective laser melting (SLM) or electron beam melting (EBM), and direct energy deposition techniques, e.g. wire- and powder laser metal deposition (LMD) [1]. These AM technologies exhibit unique process-related characteristics. The small melting pool size, relative to the AM-produced part size, results in fast cooling rates up to 1×10^6 K/s and strong melting pool dynamics, which allows the evolution of fine microstructures with reduced segregation [6]. In addition, the process-related benefits may be utilized for rapid screening of new materials, as recently suggested in [7]. Metal AM allows the rapid production of functional prototypes (rapid prototyping) up to small series production (rapid manufacturing) with the possibility of manufacturing on demand. Industries with small production numbers down to fully individual parts with complex geometries, e.g. aerospace, tooling and medical application, can benefit from shorter development cycles and reduced time-to-market [8–10].

One of the main advantages of the SLM technique is geometric freedom as it allows for the production of complex near net-shape structures directly from three-dimensional computer-aided design (3D CAD) data, addressing the future need for highly individualized parts with increased functionality, e.g. lightweight lattice structures with locally defined mechanical properties [2,11]. One example is the topologically optimized lightweight hinge bracket with integrated lattice structures in the Airbus A320, which is only economically producible when using metal AM [12]. Other metal AM-produced and consolidated parts with increased efficiency, like the fuel nozzle for the new LEAP jet engine by GE [13] and the core main injector for the development upper-stage rocket engine RL10 by Aerojet Rocketdyne [14], are already in production or were tested successfully. By taking advantage of the geometric freedom, the use of lattice structures, also referred to as meta- or architectured materials, can offer functional and mechanical properties that cannot be achieved in bulk materials [15,16]. These advantages of lattice structures have been known since long, but AM technologies made it significantly easier to manufacture these structures. Among other aspects, the design of lattice structures involves the choice of (a) the AM technology, (b) the material, (c) the lattice geometry, (d) the relative density of the lattice structure referred to bulk samples and (e) the maximal defect density of every strut and node of the lattice structure itself. In this context, we address the application of SLM for producing lattice structures made of stainless steel 1.4404. SLM is the most promising technique for becoming an option for serial production of lattice structures, due to the small achievable structure size, excellent control over the lattice geometry and the relatively high surface quality [17,18]. 1.4404 is used as a model alloy that has been widely researched in the field of metal AM, and shows high corrosion resistance and excellent weldability.

The aim of the current study is to investigate the plastic deformation behavior and the corresponding mechanical properties, especially tensile strength, compression strength, energy absorption and fatigue strength of lattice structures made of stainless steel 1.4404. Therefore, we produced two geometrically distinctly different unit lattice cells, i.e. a face-centered cubic lattice cell (Fig. 1a–d), which will be referred as f2cc,z lattice following the nomenclature of [17,19] and a hollow spherical lattice cell (Fig. 1e–h) [17] with same relative density. In this work, a unit cell is the smallest group of struts/spheres and nodes that is repeatedly built up to produce lattice structures.

As unit cells are very dissimilar, a strongly different deformation behavior is expected in the two types of lattice structures [20]. In order to investigate the deformation behavior as well as the influence of SLM-process inherent characteristics on the defect density, microstructure and element distribution, light and scanning electron microscopy (SEM) in combination with energy dispersive X-ray spectrometry (EDS) were used. Tensile, compression and fatigue tests were carried out to analyze mechanical properties. The experimental data from tensile testing of SLM-produced lattice structures were compared with SLM-produced bulk as well as conventionally produced reference specimens. In compression and tension tests, local deformation behavior was analyzed by digital image correlation (DIC). So far, combined analysis of the local strain distribution of SLM-produced lattice structures in tensile and compression tests has not been reported in previous studies. The same holds for a comparative analysis of lattice structures and bulk specimens regarding microstructure, defect density, fatigue behavior and energy abortion capacity. The plastic deformation behavior of the two lattice structures will be analyzed by considering geometrical and microstructural aspects. Implications on usability and possibility of further improving mechanical properties also will be discussed.

2. Methods

2.1. Material and processing

The chemical composition of the 1.4404 metal powder, the SLM-produced bulk and the conventionally produced reference material investigated in this study is given in Table 1. The powder metal (provided by TLS Technik GmbH & Co. Spezialpulver KG) was first ingot-cast and subsequently atomized using the EIGA-technique (Electrode Induction Melting Gas Atomization) and argon as atomizing medium to produce prealloyed powder. The powder particles constituted a spherical shape and an average size of 40 μm within a range between 25 μm and 50 μm. Hollow powder particles and significant satellites were not detected (Fig. 2). The conventionally produced reference material was hot rolled and solution annealed.

Additively manufactured bulk and lattice structure specimens for mechanical testing and microstructure analysis were produced using a SLM 280 HL device (SLM Solutions GmbH) equipped with two Yb:YAG-lasers (400 W and 700 W). Optimized process parameters for production of dense bulk and lattice structure specimens ($\rho > 99.0\%$ ρ_{th}) with a high geometric accuracy were identified by systematic variation of laser power, scan speed, layer thickness, hatch spacing and contour offset. The theoretical density (ρ_{th}) is defined as the density of fully dense bulk material without any defects. The parameter set chosen is given in Table 2.

A scan strategy with contour hatch laser beam movement within each layer and a clockwise rotation of 33° between subsequent layers was chosen. In addition some of the f2cc,z lattice structure specimens were annealed to investigate the influence of additional heat treatment on microstructure and mechanical properties. The annealing was performed at 900 °C for 1 h in an air furnace followed by water quenching.

2.2. Specimens and characterization techniques

Dimensions of the lattice unit cells (edge length, z-strut, cross-strut and hollow sphere wall diameter) are defined in Fig. 1b and f. By merging unit cells in x-, y- and z-direction lattice structure specimens for mechanical testing are constructed. Fig. 1c shows the CAD model of a cubic f2cc,z lattice structure and Fig. 1g a hollow spherical lattice structure specimen for compression testing by merging 5 unit cells in x-, y- and z-directions. It must be noted that, according to Bültmann et al. [34],