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Strength analysis and modeling of cellular lattice structures manufactured using selective laser melting for tooling applications

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ABSTRACT

Additive manufacturing is rapidly developing and gaining popularity for direct metal fabrication systems like selective laser melting (SLM). The technology has shown significant improvement for high-quality fabrication of lightweight design-efficient structures such as conformal cooling channels in injection molding tools and lattice structures. This research examines the effect of cellular lattice structures on the strength of workpieces additively manufactured from ultra high-strength steel powder. Two commercial SLM machines are used to fabricate cellular samples based on four architectures— solid, hollow, lattice structure and rotated lattice structure. Compression test is applied to the specimens while they are deformed. The analytical approach includes finite element (FE), geometrical and mathematical models for prediction of collapse strength. The results from the the models are verified with experimental data and it is shown that they agree well. The results from this research show that using lattice structures significantly reduces the strength of material with respect to solid samples while indicating no serious increase of strength compared to hollow structures. In combination with an analysis of microstructures, a description of strength analysis is obtained with respect to process parameters.

1. Introduction

Additive manufacturing has been considered a breakthrough in production systems and looked as a renaissance in manufacturing [1]. Recently, ASTM International has recommended to adopt the term additive manufacturing (AM) [2]. This defines AM as a process of joining materials to make objects from 3D model data, usually layer upon layer. Early developments in AM focused on complex polymer-based prototypes known as rapid prototyping. With the rapid developments, AM was introduced for tooling applications (rapid tooling) such as injection molding and forming tools [3]. More advances in laser-based additive solid freeform manufacturing processes posed the possibility of layer-by-layer fabrication of complex metal components where they are impossible to achieve by conventional processes. Two powder-based melting methods, known as electron beam melting (EBM) and laser beam melting (LBM); have been introduced where powder particles are selectively melted by the scanned electron and laser beam respectively.

Using material in the parts where it is needed is the basic concept for optimum cellular lattice structures. The cellular structures have several benefits for advanced lightweight engineering applications (e.g. aircraft fuselage, wings and biomedical implants). These structures offer unique thermal and mechanical properties such as high strength-to-weight ratio, high-energy absorption, and low heat conductivity. Depending on the complexity of the part, traditional ways of manufacturing of highly porous cellular metals are limited in terms of cell size and sometimes impossible for cellular lattice structures with respect to additive manufacturing technology [4]. Selective laser melting (SLM) systems are extremely versatile and allows complex metallic cellular structures to be fabricated while positioning the cells at specific locations throughout of the part. New advances in material development enabled manufacture of metallic parts by SLM procedure from ultra-high strength steels in powder form, which is ideal for tooling applications such as punching and injection molding [5]. Therefore, if an alternative to manufacture of tools can be developed using cellular-lattice-structured concept and AM to reach a lightweight structure, there is the potential to significantly improve tooling efficiency by decreasing both the material and manufacturing cost. Furthermore, achieving this goal decreases the production time of workpieces produced by the molds in high-speed applications such as micro cold forming [6,7] due to the lighter tooling system causing lower maintenance due to longer tools' lifetime.

Beginning in the late 2000s, researchers began investigating how lattice-structured materials affect the mechanical properties of metallic cellular solids [8]. As this research has progressed, it has been found that a vast number of material characteristics such as density, mechanical,

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thermal, electrical and acoustic properties can be altered using cellular structures (metal foams) while offering lightweight and sometimes cheap structures [9]. Traditionally, foams are a particular subset of lattice-structured materials. Predictability and reproducibility of mechanical properties are the big pros of metallic lattice structures [10]. In 1997, Ashby discovered that the strut-bending as the dominant mode of deformation lowers the stiffness and strength of lattice structures [11]. Deshpande et al. published a document demonstrating that stretching-governed octet-truss lattice material increases the stiffness and strength by a factor between 3 and 10 when comparing to the corresponding values for metallic foams [12]. Mines discussed on the multi-axial crush behavior of various foams and micro-lattice structures aiming to develop analytical and finite element models to simulate the progressive collapse of core materials used in sandwich construction [13]. From studies conducted by McKown [14], it was shown that mechanical properties of metallic open-cell lattice structures consisting of BCC and BCC-Z cubic-shaped unit-cell geometries are close to the theoretical optimum limits of open-cell foam model, described by Ashby et al. [9]. It was also discovered that using z rods in the BCC-Z unit-cell, the resistance increased in compression test to a great extent than it is possible by octahedral cells. Moreover, Tsopanos et al. showed a linear relationship between mechanical properties and combination of manufacturing parameters of laser power and laser exposure time for manufacturing of open-cell structures using BCC unit-cell [15]. Gorny et al. reported on the effects that local strain concentration, process-induced pores and the microstructure had on failure behavior of the TiAl6V4 BCC unit-cell lattice structure [16]. In 2012, Yan et al. investigated the effect of gyroid unit-cell type on the manufacturability, density and mechanical properties using compression test, microcomputer tomography and Scanning Electron Microscopy (SEM) [17]. Additionally, Smith et al. explored compressive response of lattice structures consisting of BCC and BCC-Z unit-cell shapes using finite element method when varying both the relative density and the aspect ratio of the unit cell [18]. They also reported on a reverse engineering approach for estimation of the effective strut diameter of the lattices due to the the variation of the dimensions and struts diameter along their length caused by the nature of SLM procedure. Gümrük et al. developed theoretical, experimental and numerical analyses for stainless steel micro lattice structures using Timoshenko beam model, systematic compression test and 3D finite element analyses respectively [19]. In 2014, Karamooz Ravari et al. reported on the effect the variation of the struts' diameter had on elastic modulus and collapse stress of cellular lattice structures using FE modeling [20]. While the study by Yan et al. showed possibility of manufacturing the lattice structure with struts with an angle 0 compared to the building plane as the worst building orientation for SLM [21], the study by Wauthle et al. found that horizontal struts include lots of porosities causing early failure of the structure [22].

Regarding material development for tooling applications, previous studies have indicated the ability of SLM systems to fabricate parts from tool steels such as M2 and H13 [23,24]. The high strength tool steels in fine powder form have been tested and some are commercially available in the market [25].

Lattice materials are an array of cells making up of struts while connecting between two nodes each rigidly bonded or pin-jointed. Either the cell face can end up with solid or void leading to closed-cell or open-cell lattice structures while excluding walls of cells. Therefore, the lattice structure is comprised of a web of struts or a solid shell around the web. The material, cell shape and relative density ρ/ρ_s (where ρ and ρ_s are the density of cellular material and the solid respectively) are the key process parameters determining properties of cellular materials. The purpose of these materials is to make stiff structures using unit cells where they are useful such that the new material is as light as possible. By doing so, the strength and stiffness of the material becomes weaker, when the amount of material required to fabricate the part is reduced. The second goal of the cellular structures is to increase maximum achievable functionality of the component of which the lattice used such as energy absorption, large strain, stiffness and strength.

The main aim of this study is to obtain an insight into using cellular lattice structures for high performance bear loading constructions such as mold components when compared to solid and hollow structures. The solid structure represents the conventional way of tool construction when hollow sample determines the state of structure with no cellular lattices. The current research involves methods for strength analysis of structures additively manufactured in order to maximize the strength and minimize the weight of the components to be utilized in tooling applications, thereby reducing both the manufacturing time and material cost of tools. More specifically, the research examines how the cellular lattices increase the efficiency of the tooling structures when applying compression load. To examine this possibility, it is important to design a combination of structures for specimens (four architectures will be examined as part of this study). A further purpose of this research is to model accurately the collapse strength of hollow and cellular lattice structures manufactured using SLM under compression load. FE, geometrical and mathematical models are used and analytical predictions are compared to experimental tests.

2. Material and methods

2.1. Lattice structures

In a study conducted by Rehme and Emmelmann, the effect of uniaxial compressive test on cellular structures with eight different cell types was investigated [26]. This research involved finding optimal unit cell type in order to maximize the collapse strength and minimize the overall achievable density. A cell type named F_2CC-Z got the best ratio for collapse strength-to-density. This unit cell consisted of rods in vertical direction and double-faced diagonals as shown in Fig. 1. As previously mentioned, the presence of vertical struts enhances the strength of lattice structure [14]. In subsequent studies, it was discovered that the orientation of single struts along the flux of force prevents unwanted bending loads on the lattice structure, thereby appearing only push and pull force in the structure [27]. To increase the strength of testing structures in z direction, the unit cell F_2CC-Z was modified in order to maximize the number of z rods with five vertical and eight body-centered rods in this research (Fig. 1). Similar unit cell shape was used to model the behavior of plastic lattice structures manufactured using fused deposition modeling under compression load [20].

2.2. Experimental setup

The samples used in this study are cylinders of 28 mm diameter and 46 mm height. The lattice structure is created by cubic unit cells with the edge length of 4 mm and strut diameter of 0.73 mm. In order to determine more exactly the effect of lattice structures on strength, four combinations of specimens were examined, as shown in Fig. 2. This includes solid, hollow, closed-cell non-rotated (ST) and closed-cell rotation of 30° (ST-30) samples. Tools generally include several features (depending on the application) such as holes for punch holders, tool inserts, contours and cooling channels. Therefore, the cellular and hollow samples have a wall thickness of 5 mm in all sides.

Two commercial SLM systems (called Laser 1 and Laser 2 in this research) produced the same combination of the samples using process parameters listed in Table 1. To verify the repeatability of the results, three specimens were tested for each sample structure/SLM system combinations. In total, 12 samples were manufactured by each SLM machines for the tests.

Four small holes on the bases indicate the exits for depowdering phase of the manufacturing process. The four straight rods inside the hollow samples (Fig. 2) were required to support the “roof” of the cylinder since surfaces with an angle less than 45° compared to horizontal require support in one way or another [28,29]. The 4 rods were designed