Journal of Materials Processing Technology 214 (2014) 856–864

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

Evaluation of light-weight AlSi10Mg periodic cellular lattice structures fabricated via direct metal laser sintering

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ARTICLE INFO

Article history:
Received 8 July 2013
Received in revised form
21 November 2013
Accepted 6 December 2013
Available online 15 December 2013

Keywords:
Additive manufacture
Direct metal laser sintering
Aluminium alloy
Periodic cellular lattice structures
Morphology
Compression test

ABSTRACT

Aluminium alloy porous structures are highly demanded for many applications such as light-weight aerospace and heat exchanger products. Conventional manufacturing methods such as casting, however, faces difficulty in making aluminium alloy complex periodic cellular lattice structures with designed unit cell shape and size and volume fraction. This study evaluates the manufacturability and performance of AlSi10Mg periodic cellular lattice structures fabricated via direct metal laser sintering (DMLS). Various lattice structures at different volume fractions and unit cell sizes are designed by repeating a unit cell type called “diamond”. Due to the self-supported feature of the diamond unit cell, low volume fraction (7.5–15%) AlSi10Mg periodic cellular lattice structures can be fabricated by the DMLS process with the unit cell sizes ranging from 3 mm to 7 mm. A good geometric agreement is found between the original design structure models and the DMLS made structures, but the strut sizes of the DMLS made structures are slightly higher than the designed values and thus pore sizes decrease. There is clear relationship between the compressive modulus and strength of the structures and their volume fraction and unit size. Hence, this study shows that light-weight aluminium structures can be designed and made with the controlled unit size and volume fraction and the predicted mechanical properties.

1. Introduction

Light-weight metal cellular structures are a unique classification of materials. They can offer high performance features such as high strength accompanied by a relatively low mass, good energy absorption characteristics and good thermal and acoustic insulation properties (Nakajima, 2007). Metal cellular structures are formed as two common types: stochastic porous structures and periodic cellular lattice structures. Metal stochastic porous structures typically have a random distribution of open or closed voids, whereas metal periodic cellular lattice structures have uniform structures that are based on repeating unit cells. In general, periodic structures show superior mechanical properties (i.e. energy absorption, strength and stiffness), easier control of structure properties, better load sustaining capabilities and higher surface area densities than the stochastic porous structures (Williams et al., 2011). Therefore, metal periodic cellular lattice structures can be used to develop light-weight structures that can provide advanced or multifunctional performance for high value engineering products such as automobile, aerospace and medical products (Zhou et al., 2004). These periodic lattice structures, however, currently face a higher manufacturing complexity than the stochastic structures. It can be time and cost consuming to use conventional methods (i.e. investment casting, deformation forming, metal wire approaches, brazing etc.) to make periodic cellular lattice structures. The structures made by conventional methods possess relatively simple geometries and limited design freedoms, and consequently lack advanced functionality to meet more advanced requirements and applications.

Additive manufacturing (AM) is able to make three-dimensional objects with virtually any shape from computer-aided design (CAD) models, and thus have been used to fabricate cellular structures with controlled internal structures and complex external shapes extensively in the past few years. For example, Heinl et al. (2008) built cellular Ti-6Al-4V structures with interconnected macro porosity for bone implants by selective electron beam melting. Direct metal laser sintering (DMLS) or selective laser sintering (SLM) is the powder bed fusion (PBF) process of AM technologies and capable of producing fully-dense metal components with complex freeform geometry directly from computer-aided design

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http://dx.doi.org/10.1016/j.jmatprotec.2013.12.004

(CAD) models (Louvis et al., 2011). DMLS selectively melts successive layers of metal powders to form net-shape components, and shows great potential to manufacture metal periodic cellular lattice structures with fine features at a high resolution. DMLS or SLM has been recently employed to build metal cellular lattice structures using several metal materials including stainless steel, pure titanium, and titanium alloy. Some researchers investigated the manufacturability and mechanical properties of stainless steel cellular lattice structures with various unit cell geometries and cell sizes. For instance, McKown et al. (2008) manufactured a range of 316L stainless steel lattice structures based on two types of unit cells, possessing octahedral and pillar-octahedral topologies respectively, by the SLM process, and studied the compression and blast loading behaviour of these lattice structures. Our previous work (Yan et al., 2012) evaluated the manufacturability and compression properties of 316L stainless steel periodic cellular lattice structures using a 'gyroid' type unit cell and found that the unit cell has self-supported feature so that a wide unit cell size range of 2–8 mm can be built by SLM without obvious deformations. Rehme and Emmelmann (2009) used the SLM process to build some honeycomb structures that were designed to have negative Poisson's ratio. A few studies attempted to fabricate pure titanium and titanium alloy periodic cellular lattice structures with interconnected pores for medical applications such as bone implants because the mechanical properties of periodic lattice structures can be tailored to match those of natural bones. For example, Mullen et al. (2009) manufactured cellular titanium structures based on an octahedral unit cell through the SLM for the purpose of bone in-growth applications, and the produced structures possessed the porosity of 10–95% and compressive strength of 0.5–350 MPa comparable to the typical naturally occurring range of natural bones; Bertol et al. (2010) reported the DMLS process and its constraints for the production of customized implants in titanium alloy with complex geometry and internal periodic lattice structures. Although DMLS or SLM has been applied to make lattice structures using the metal materials of stainless steel, titanium and its alloy, there is no report on its application to manufacture aluminium alloy cellular structures with low volume fractions and light-weight performance.

Nowadays, aluminium alloy cellular structures has been widely used for many applications such as car body structures, motorway sound insulation, heat exchangers and light weight conformal pressure tanks (Wang et al., 2006), and for instance, it was reported that aluminium foams offer good damage tolerance, energy-absorbing capability and cost-effective performance as structural automotive parts that are up to ten times stiffer and 50% lighter than equivalent parts made of steel (Ashby et al., 2000). While aluminium open cellular structures have been commercially available for several decades, there is little report on the aluminium alloy periodic cellular lattice structures due to the limitations of the conventional manufacturing methods. Duocel aluminium open-cell foam belongs to designed cellular structures. The manufacturing process based on investment casting is as follows. An open-cell cellular polymer foam is first formed and then filled with a slurry of heat resistant material. After drying the polymer is removed and a molten aluminium alloy is cast into the resulting cavity. When the mould material is mechanically removed, an aluminium cellular structure remains (Körner and Singer, 2000). However, as described above, this manufacturing process is complicated and time- and cost-consuming, leading to the high price of Duocel foam and difficult process control.

The objective of this study is to directly make light-weight aluminium alloy periodic cellular lattice structures according to designed CAD model using emerging DMLS process. In previous studies on the DMLS of the stainless and titanium structures, the unit cell possesses straight beam-like struts and a polyhedral core. This results in a constraint in making low volume lightweight structures. It was found that low volume fractions with large unit cell size did not exhibit good manufacturability because the long overhanging struts in big unit cells would lead to the occurrence of serious deformation during the DMLS processes. This study investigates the manufacturability of periodic cellular lattice structures generated by repeating a new unit cell type called "Schwartz Diamond", referred to as diamond unit cell, via the DMLS process. It designs and utilizes the specific "self-support" characteristics of the diamond unit cell to enable the DMLS manufacturability of aluminium alloy, AlSi10Mg, periodic cellular lattice structures with wide ranges of the cell size and volume fraction. The external and internal characteristics and compression properties of DMLS-manufactured lattice structures were evaluated.

Table 1
Chemical composition of AlSi10Mg.

Alloying element	Al	Si	Cu	Mn	Mg	Zn	Fe
wt%	Rest	9–11	$\leq$0.05	$\leq$0.45	0.2–0.45	$\leq$0.10	$\leq$0.55

2. Experimental methods

2.1. Materials

The periodic cellular lattice structures were made from an AlSi10Mg alloy powder, which was purchased from Electro Optical System (EOS) GmbH, Germany. AlSi10Mg alloy, as a commonly used aluminium alloy, has the features of light-weight and excellent thermal conductivity and its composition can be found in Table 1. Fig. 1 depicts the SEM image of the AlSi10Mg alloy powder. The powder has a nearly spherical shape and smooth surfaces, which lead to a good flowability. The particle size of the powder is in the range of 5–20 μm.

2.2. Design of 'diamond' periodic cellular lattice structure

The CAD models of diamond unit cell and cellular lattice structures were generated through the +CAD software provided by Simpleware Ltd., UK, and shown in Fig. 2(a) and (b), respectively. The computational method used to generate cellular lattice structures was reported in our previous work (Hao et al., 2012). Diamond lattice structures are mathematically defined, allowing precise control of volume fraction and unit cell size in the creation of an interconnected network. Volume fraction is defined as the volume

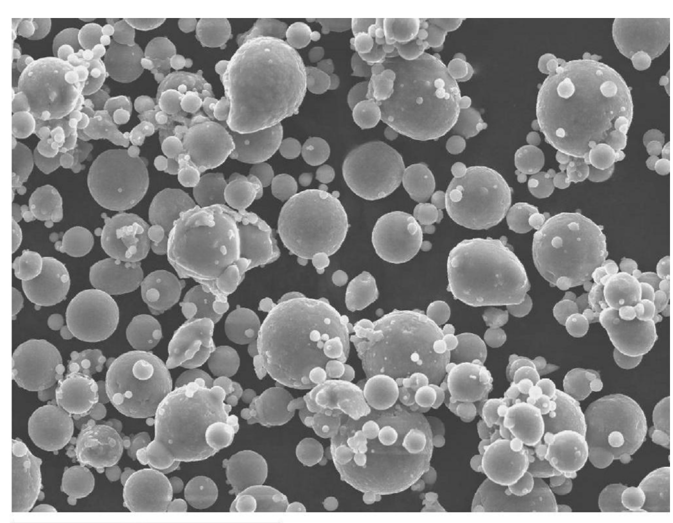

Fig. 1. SEM image of the AlSi10Mg alloy powder.