Materials and Design 98 (2016) 344–357

Contents lists available at ScienceDirect

Materials and Design

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

Selective laser melting (SLM) of AlSi12Mg lattice structures

Martin Leary [a,*], Maciej Mazur [a], Joe Elambasseril [a], Matthew McMillan [a], Thomas Chirent [b], Yingying Sun [a], Ma Qian [a], Mark Easton [a], Milan Brandt [a]

[a] RMIT Centre for Additive Manufacture, RMIT University, Melbourne, Australia
[b] Institut Français de Mécanique Avancée, Clermont-Ferrand, France

ARTICLE INFO

Article history:
Received 26 October 2015
Received in revised form 26 February 2016
Accepted 29 February 2016
Available online 6 March 2016

Keywords:
Additive manufacture
Lattice structures
Selective laser melting
Aluminium
AlSi12Mg
Optimisation
Design for additive manufacture

ABSTRACT

Additive manufacture (AM) enables innovative structural design, including the fabrication of complex lattice structures with unique engineering characteristics. In particular, selective laser melting (SLM) is an AM process that enables the manufacture of space filling lattice structures with exceptional load bearing efficiency and customisable stiffness. However, to commercialise SLM lattice structures it is necessary to formally define the manufacturability of candidate lattice geometries, and characterise the associated mechanical response including compressive strength and stiffness. This work provides an experimental investigation of the mechanical properties of SLM AlSi12Mg lattice structures for optimised process parameters as well as the manufacturability of lattice strut elements for a series of build inclinations and strut diameters. Based on identified manufacturability limits, lattice topologies of engineering relevance were fabricated, including both stretch-dominated and bending-dominated structures. Manufactured lattice morphology and surface roughness was quantified, as were the associated mechanical properties and deformation and failure behaviour.

1. Additive manufacture and selective laser melting

Additive manufacturing (AM) refers to the process of fabricating near-net components from unit materials [1] in a layerwise manner. AM differs fundamentally from "subtractive manufacturing methodologies, such as traditional machining" [2], and has been labelled as a disruptive technology [3]. The disruptive nature of AM enables a series of technical and economic advantages, including: enhanced cost-competitiveness for low volume production [4]; reduced environmental impact of manufacture [5]; and, increased design complexity [3,6].

AM is based on a digital representation of product geometry. This representation typically consists of tessellated triangular facets, known as a Stereolithography (STL) file [7,8]. However, enhanced data structures are also proposed that are more compatible with specific AM requirements, such as STL 2.0 [9], Additive Manufacturing Format (AMF) [10] and Bezier STL [11].

Selective laser melting (SLM) is a powder-bed AM technology that uses a scanning laser to sequentially melt layers of powdered metal under an inert atmosphere [12]. The significant advantage of SLM technology includes high flexibility and achievable component complexity, enabling the fabrication of highly complex lattice structures that are not otherwise manufacturable [13]. Such lattice structures enable structural optimisation [14], while reducing associated manufacture time and materials costs by minimising component volume [15].

SLM material research is typically focused on titanium alloys due to their high corrosion resistance, high specific strength [16–22] and biocompatibility [23]. These favourable properties have enabled a range of technical SLM titanium applications, including: customised load bearing medical implants [24,25], lattice structures with mechanical properties optimised for compatibility with bone [26], high-value aerospace [27]; space [28], and automotive applications [29].

Although aluminium alloys are not biocompatible, they exhibit a number of properties that make them eminently suitable for commercial AM applications, including:

- Aluminium (2.7 g/cm^3) has significantly lower density than titanium (4.5 g/cm^3), thereby enabling commercial opportunities in scenarios that benefit from mass reduction. The mass reduction advantage of AM aluminium lattice structures is especially relevant for non-stationary scenarios such as automotive and aerospace where the fuel consumption associated with component mass is significant [30].
- The high strength-to-weight ratio of aluminium enables optimisation for structural applications, especially for structures subject to bending loads such as beam and plate applications [31]. This outcome is particularly relevant to the optimisation of AM lattice structures, which are subject to significant bending, either during elastic loading (in the case of under-stiff structures) or plastic collapse (in the case of just-stiff and over stiff structures) (Section 3).
- The fatigue-strength of aluminium, in combination with low material density, results in optimal material selection for weight limited design where the number of loading cycles is below, or close to the

* Corresponding author.
E-mail address: martin.leary@rmit.edu.au (M. Leary).

http://dx.doi.org/10.1016/j.matdes.2016.02.127

Nomenclature

Term	Definition
AM	Additive manufacture
CT	Computed tomography
BCC	Body centred cubic unit cell
BCCZ	Body centred cubic unit cell with (vertical) Z-struts
DOE	Design of experiments
FBCCZ	Face and body centred cubic unit cell with (vertical) Z-struts
FCC	Face centred cubic unit cell
FCCZ	Face centred cubic unit cell with (vertical) Z-struts
FEA	Finite element analysis
SLM	Selective laser melting

Symbols

Term	Definition
D_v	Volume weighted percentile particle diameter
$D_{[3,2]}$	Surface area moment mean (Sauter Mean Diameter)
$D_{[4,3]}$	Volume moment mean (De Brouckere Mean Diameter)
E	Lattice specimen modulus [MPa]
E_s	Solid material modulus [MPa]
h	Hatch spacing [μm]
j	Roughness sample index
k_R	Relative stiffness
M	Maxwell number
n	Number of nodes
N	Number of roughness measures per sample, number of test specimens
ρ	Lattice specimen density [kg/m^3]
ρ_c	Lattice unit cell density [kg/m^3]
ρ_s	Lattice solid material density [kg/m^3]
P	Laser power [W]
R_a	The average surface roughness [μm]
R_t	The distance between the maximum peak and minimum valley [μm]
R_z	The peak to peak roughness [μm]
s	Number of struts
σ	Lattice specimen compressive strength [MPa]
σ_s	Solid material compressive strength [MPa]
t	Layer thickness [mm]
v	Scan speed [mm/s]
Υ	Laser energy density [J/mm^3]
W	Volumetric energy absorption [MJ/m^3]

endurance limit [30]. The robust design of fatigue-optimised AM lattice structures is an active research domain [32,33] that will enable commercially relevant innovation in the design of fatigue-limited aluminium lattice structures.

- The high thermal diffusivity of aluminium alloys combined with the capability of AM for complex part geometry enables the fabrication of high-efficiency thermal devices, including heat sinks and heat exchangers [34,35].
- Aluminium has excellent resistance to corrosion [36], enabling engineered aluminium lattice structures to be applied in corrosive environments, for example in [37]: architectural and marine applications; faying surfaces in automotive and aerospace applications, and in the design of heat-exchangers in direct contact with corrosive fluids.
- Aluminium has relatively high electrical conductivity [38], enabling its application in electrically conductive devices. The combined electrical, structural and lightweight properties of aluminium enable the fabrication of high-value components that combine both electrical and structural function, for example in self-supporting lightweight electrical conductors [39].
- Importantly, aluminium alloys often provide a lower cost to achieve a specified load bearing function in comparison to titanium [30], and therefore provide an opportunity for the economical commercialisation of AM technologies, especially in non-stationary applications.

Despite the commercial opportunities associated with aluminium lattice structural design in SLM, there appears to be sparse available research in comparison with titanium. This lack of research may be in part due technical challenges in SLM of aluminium powders, including poor powder flowability, high laser reflectivity and oxidation of aluminium during melting [40].

2. SLM processing and properties

SLM is a highly complex multiphysics process, due to: large thermal gradients [41]; complex three-dimensional geometries [42]; local overheating [43,44]; local heat transfer paths that are temporally and spatially transient [45,46]; and, thermal powder bed resistance that is poorly understood and subject to significant experimental uncertainty [47,48]. SLM is highly dimensional, with nearly 130 variables of influence on final component quality [49,50].

Processing parameters that determine the laser energy density (Eq. (1)) are: laser power, P, laser scanning speed, v, hatch spacing, h, and the layer thickness, t.

$$\Upsilon = \frac{P}{h \cdot v \cdot t} \quad \begin{array}{l} \text{Where :} \\ \Upsilon : \text{energy density } [J/mm^3] \\ P : \text{laser power } [W] \\ v : \text{scan speed } [\mathrm{mm/s}] \\ t : \text{layer thickness } [\mathrm{mm}] \\ h : \text{hatch spacing } [\mathrm{mm}] \end{array} \quad (1)$$

2.1. SLM processing of aluminium alloys

Aluminium alloys provide significant technical and economic opportunities due to their favourable strength-to-weight and cost-to-weight attributes. Aluminium-Silicon alloys are strong candidates for SLM due to their robust welding characteristics and small difference between liquidus and solidus temperatures [51]. However, in-comparison with titanium alloys, very little research exists on the processing of aluminium by SLM [52]. A review of the available literature has identified the following research of interest:

- Kempen et al. [51] found that for AlSi10Mg (mean particle size: 16 and 48 μm), the manufactured part quality varies with powder morphology, size and chemical composition.
- Olakanmi et al. [53] assessed the effects of SLM process parameters on the degree and orientation of porosity in Al-12Si (Particle size distribution: 45-75 μm).
- Dadbakhsh and Hao [54] investigated the manufacturability of numerous aluminium-based powders, including commercially pure aluminium, AlSi10Mg, Al Mg1SiCu, mixed with 15 wt% Fe_2O_3, and found AlSi10Mg to have the highest density due to low thermal conductivity and oxide layer breakdown; a nano-scale dendritic structure was observed leading to high hardness.
- Dadbakhsh and Hao [55] investigated SLM of numerous aluminium-based powders including: Al-5FeO3, Al-10FeO3, Al-15FeO3, and found that Hot Isostatic Pressing (HIP) increased density but did not eliminate all porosity due to the formation of oxide bands.
- Buchbinder et al. [56] found that for AlSi10Mg, high laser power and scan velocity enabled a build rate of 21mm^3/s with 99.5% density (420 MPa and 145 HV).
- Brandl et al. [57] found that for AlSi10Mg with a particle size distribution of 25–40 μm, post manufacture heat treatment has the greatest effect on fatigue limit whilst orientation has a relatively smaller effect.