Journal of Manufacturing Processes 35 (2018) 492–499

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

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

Pulsed SLM-manufactured AlSi10Mg alloy: Mechanical properties and microstructural effects of designed laser energy densities

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ARTICLE INFO

Keywords:
Laser energy density
Microstructure
Mechanical properties
Pulsed selective laser melting
AlSi10Mg

ABSTRACT

The effects of laser energy densities on microstructures and mechanical properties of AlSi10Mg samples fabricated by pulsed selective laser melting (P-SLM) were studied. Scanning electron microscope, transmission electron microscope, X-ray diffraction, Vickers hardness tester and electronic testing machine were used for analysis and measurement of microstructures, phases and mechanical properties of the samples, respectively. The results show that fine cellular microstructures are composed of α-Al, eutectic Si, and secondary Si. Moreover, the microhardness values of the specimens perpendicular to the building directions fluctuate between $HV_{0.1}110 \sim HV_{0.1}130$ while those of the specimens along the building directions decrease with increasing building heights. Finally, comparison of the mechanical properties of P-SLM and casting samples were discussed, the better mechanical properties of P-SLM samples were showed than those of the casting samples, which can be attributed to solid solution strengthening, grain refinement strengthening, dislocations strengthening and second-phase strengthening.

1. Introduction

Aluminum alloys have been ideal lightweight materials because of their excellent specific strength and stiffness, high thermal and electrical conductivity, and fine formability [1]. Hypoeutectic AlSi10Mg is increasingly employed in automotive, aerospace, and aircraft applications for its excellent casting properties, good mechanical properties and corrosion resistance [2,3]. At present, engineering parts made in AlSi10Mg have been fabricated by traditional manufacturing processes such as casting, forging, extrusion, and powder metallurgy. However, some AlSi10Mg alloy parts are normally in complex and irregular configurations, which are difficult to fabricate using the conventional processing methods. Furthermore, the low solidification rates associated with these processes may result in coarsened microstructures with the attendant poor mechanical properties and the large degrees of segregation [4]. Therefore, new processing methods are highly demanded to satisfy the need for obtaining complex components with fine and uniform microstructures.

Additive manufacturing (AM), also known as 3D printing, is a revolutionary digital and green intelligent manufacturing technology based on the design of 3D CAD model and cumulative layered deposition [5,6,7]. A type of AM fabrication known as selective laser melting (SLM) exhibits an exciting potential application in direct fabricating three-dimensional parts with complex structures [8]. Moreover, parts fabricated by SLM can also obtain very fine microstructures with the attendant high strength and hardness due to the rapid solidification rate (up to 10^{6-8} K/s) [9,10]. Kempen et al. [11] researched mechanical properties of AlSi10Mg produced by SLM. They found that SLM AlSi10Mg parts have mechanical properties higher or at least comparable to the casted AlSi10Mg material, because of the very fine microstructure and fine distribution of the Si phase. Brandl et al. [12] researched microstructure of AlSi10Mg samples manufactured by SLM, and found the microstructure was characterized by cellular dendrites of α-Al and interdentritic Si particles. Thijs et al. [13] investigated fine-structured aluminum products with controllable texture by selective laser melting of pre-alloyed AlSi10Mg powder. They observed that the high thermal gradients occurring during SLM lead to a very fine microstructure with submicron-sized cells and a high hardness. Furthermore, a morphological and crystallographic texture is present in the SLM parts. Read et al. [14] studied process optimization and mechanical properties of AlSi10Mg alloy using SLM, they concluded that samples showed better strength and elongation properties, compared to

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https://doi.org/10.1016/j.jmapro.2018.09.007
Received 12 November 2017; Accepted 3 September 2018

Table 1
Chemical composition of AlSi10Mg powders.

Element	Cu	Mg	Fe	Si	Mn	Zn	other	Al
Composition (wt %)	0.06	0.623	0.08	9.628	0.01	0.03	< 0.2	Balance

die cast Al-alloys of similar composition.

Above investigations reported the characteristics of microstructures and mechanical properties of AlSi10Mg samples fabricated by a continuous-wave SLM equipment under different process parameters. In this study, a new pulsed SLM (P-SLM) process is proposed. Moreover, microstructure evolutions and mechanical properties of AlSi10Mg using P-SLM by designed laser energy densities are presented. The strengthening mechanisms of mechanical properties are also discussed.

2. Experimental methods and materials

2.1. Powder properties and P-SLM process

The AlSi10Mg powder used in current investigation was argon gas atomized and the powder chemical composition is listed in Table 1.

The P-SLM experiments are carried out by a powder-bed manufacturing machine (provided by Chongqing Institute of Green and Intelligent Technology, Chinese Academy of Sciences). This machine can handle reactive materials in a good controlled argon atmosphere. It is equipped with a 400 W fiber laser and has a laser beam diameter of about 118 μm A meander scan strategy (raster with 67° rotation for each layer) and an aluminum substrate was used for all tests, and the platform temperature was maintained at 160 °C during the whole P-SLM process to reduce residual stresses and distortion of the components. Exposure time and point distance are in the range of 100 ~ 180 μs, and 80 ~ 180 μm respectively.

The laser energy density (LED) describes the effective energy input per volume during P-SLM [15,16]:

$$LED = P/(vhd) \tag{1}$$

where P (W) denotes the laser power, v (mm/s) the scanning velocity, h (mm) the distance between the individual hatch vectors and d (mm) the slice thickness of the individual layers. The LED represents the energy absorbed by unit volume of powders. Further, the scanning velocity v is determined by:

$$v = Pd/Te \tag{2}$$

where Pd (μm) is the point distance and Te (μs) is the exposure time. Therefore, a formula can be drawn that:

$$LED = PTe/(Pdhd) \tag{3}$$

In this study, P = 400 W, h = 0.13 mm, d = 0.025 mm. Consequently,

$$LED = 8 \times 10^5 Te/(7Pd) \tag{4}$$

The LEDs in the SLM process are calculated according to Eq. (4), and typical LED of 89, 109, 131, 174 and 200 J/mm^3 were selected and analyzed in the experiment.

2.2. Microstructure and fracture surface analyses

The cubic sample with dimensions of 10 mm × 10 mm × 10 mm was manufactured. Cross-sections of the specimens were prepared by standard metallographic procedures, including wire cutting, grinding, polishing and etching (vol. 1%HF + vol. 1.5%HCL + vol. 2.5%HNO_3 + vol. 95%H_2O). Microstructure micrographs and fracture surfaces of the SLM processed specimens were obtained using an optical microscopy (Zeiss, Axio Scope.A1) and a field emission scanning electron microscope (JEOL, JSM-7800 F). Energy dispersive X-ray spectroscopy (Oxford, Inc., ISIS300 EDS) was used to detect the elemental distributions and help to determine the phases formed in the SLMed samples. A field emission transmission electron microscope (Tecnai, G2 F30) was used to characterize diffraction patterns. X-ray diffraction (XRD) (using Cu Ka, Panalytical Xpert Pro diffractometer) was used to identify the phases formed in the samples.

2.3. Mechanical properties testing

The Micro-Vickers hardness tests were performed by a Vickers hardness tester (MTH4 microhardness-tester) with a period of 20 s, a load of 100 g and a step size of 0.5 mm. At least twenty measurements were made at X, Y and 45° direction, respectively. Tensile tests were carried out with an electronic testing machine (SANS XYA105C) at room temperature with measuring length of 66 mm, according to EN 10002-1. The vertically and horizontally built samples were tested along their axis and the tensile velocity was 0.5 mm/min. Three tensile test results were collected for every type of specimen and the average values were adopted as results. The dimensions for the tensile specimens were made in two build direction, as illustrated in Fig. 1.

3. Results

3.1. Microstructures

Typical microstructures of the AlSi10Mg parts perpendicular to building directions produced by P-SLM are shown in Fig. 2. The interlayer microstructure features (as seen in Fig. 2(a)) created by the pulsed laser beam has distinguished difference with the elongated teardrop shape molten pool microstructures caused by continuous-wave laser beam movement reported in previous literature [17], the obvious layered structure can be observed, and the elliptical molten pools overlapping each other toward the direction of laser movement. The pulse laser has tens of millisecond gaps between each pulse due to its

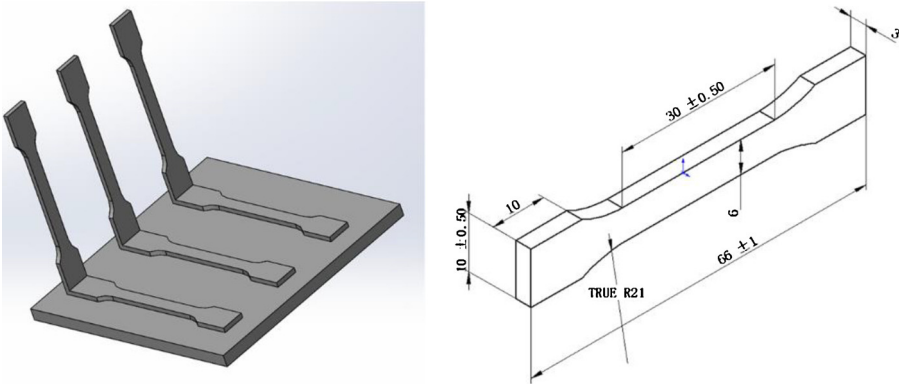

Fig. 1. Diagram of the vertically and horizontally built samples and dimensions for the tensile specimens.