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The microstructure and mechanical properties of selectively laser melted AlSi10Mg: The effect of a conventional T6-like heat treatment

Nesma T. Aboulkhair [a,b,*], Ian Maskery [a], Chris Tuck [a], Ian Ashcroft [a], Nicola M. Everitt [a]

[a] Additive Manufacturing and 3D Printing Research Group, Faculty of Engineering, University of Nottingham, Nottingham NG7 2RD, United Kingdom
[b] Bioengineering Research Group, Faculty of Engineering, University of Nottingham, Nottingham NG7 2RD, United Kingdom

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ABSTRACT

Selective laser melting (SLM) of aluminium is of research interest because of its potential benefits to high value manufacturing applications in the aerospace and automotive industries. In order to demonstrate the credibility of SLM Al parts, their mechanical properties need to be studied. In this paper, the nano-, micro-, and macro-scale mechanical properties of SLM AlSi10Mg were examined. In addition, the effect of a conventional T6-like heat treatment was investigated and correlated to the generated microstructure. Nanoindentation showed uniform hardness within the SLM material. Significant spatial variation was observed after heat treatment due to phase transformation. It was found that the SLM material's micro-hardness exceeded its die-cast counterpart. Heat treatment softened the material, reducing micro-hardness from 125 ± 1 HV to 100 ± 1 HV. An ultimate tensile strength (333 MPa), surpassing that of the die cast counterpart was achieved, which was slightly reduced by heat treatment (12%) alongside a significant gain in strain-to-failure (~threefold). Significantly high compressive yield strength was recorded for the as-built material with the ability to withstand high compressive strains. The SLM characteristic microstructure yielded enhanced strength under loading, outperforming cast material. The use of a T6-like heat treatment procedure also modified the properties of the material to yield a potentially attractive compromise between the material's strength and ductility making it more suitable for a wider range of applications and opening up further opportunities for the additive manufacturing process and alloy combination.

1. Introduction

Selective laser melting (SLM) is a layer-based additive manufacturing technology that is utilised to manufacture complex and customised structures from metal powder. The main advantage of this process over conventional manufacturing methods is the facility to create lightweight parts, such as those which result from topology optimisation [1,2] or include lattice structures [3–5] to replace bulk solids. SLM saves resources, reduces waste and carbon footprint [6,7]. SLM also makes it possible to manufacture parts from materials that can be difficult to machine [8]; such as AlSi10Mg, which, due to the presence of the hard Si phase, is mainly used in casting.

Aluminium alloys are attracting the attention of SLM users because of their wide use across many industrial sectors; aerospace and automotive being two examples. However, processing Al alloys with SLM can be challenging because of the material's high reflectivity [9] and thermal conductivity [10], which can lead to high levels of porosity. There have been a number of previous studies concerned with parameter optimisation to produce close to fully dense parts from Al alloys using SLM, such as [11–16]. In addition, several studies have been dedicated to formulating the mechanisms of pore formation and developing means of porosity reduction, such as [12,17]. The use of high laser power (up to 1 kW) was recommended by Buchbinder et al. [14], whereas Aboulkhair et al. [12] used a pre-sinter scan strategy (multiple scans per layer) to reduce porosity significantly (from 97.74% to 99.82%) whilst using relatively low laser power.

The manufacture of load bearing parts using SLM is being considered in numerous applications and consequently, the mechanical performance of SLM parts is gaining further attention. SLM of Al alloys produces a characteristically fine microstructure [18] that has been shown to yield mechanical behaviour significantly different from that seen in conventionally cast material [19], which usually has a coarser microstructure. There are several

* Corresponding author at: Additive Manufacturing and 3D Printing Research Group, Faculty of Engineering, University of Nottingham, Nottingham NG7 2RD, United Kingdom.
E-mail address: nesma.aboulkhair@nottingham.ac.uk (N.T. Aboulkhair).

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aspects that require consideration when studying the mechanical behaviour of SLM parts. Although the effect of build orientation has been reported as influential on the tensile properties of Ti alloys [20], it has less influence in the case of AlSi10Mg; mainly affecting elongation under tensile loading [19,21]. The energy density delivered to the material during processing also affects the mechanical properties. Various mechanical properties of SLM parts made from Al alloys have been reported in the literature, such as tensile behaviour [19,22–24], micro-hardness [21,23], impact resistance [21], and fatigue performance [22,25]. Read et al. [19] showed that the tensile strength of SLM AlSi10Mg is higher than that of the die cast counterpart, but the latter has better ductility. Siddique et al. [22] investigated the effect of the energy density, build plate preheating, and post processing stress relief on the tensile properties of SLM AlSi12, reporting that the energy density had the strongest influence. Kempen et al. [21] reported a higher hardness for SLM AlSi10Mg when compared to the die-cast equivalent as well as improved impact resistance. The fatigue life of SLM Al alloys was found to be affected by porosity or the presence of un-bonded regions in the samples [22]. As for the compressive behaviour of SLM Al alloys, the attention has mainly been directed to studying the latticed structures [26], to the authors' knowledge, this study is the first to report on the compressive behaviour of solid SLM AlSi10Mg.

Altering the mechanical properties of SLM materials by heat treatment usually follows the procedures that have been developed for conventionally manufactured materials, with no special attention to the distinct microstructure that SLM produces. For example, Brandl et al. [25] enhanced the fatigue performance of SLM AlSi10Mg using a T6 heat treatment, a process including solution treatment, water quenching, and artificial ageing, which they referred to as "peak-hardening". Prashanth et al. [24] reported microstructure coarsening and material softening when annealing SLM AlSi12, which is the same response as conventionally cast material. Importantly, according to Aboulkhair et al. [27], a conventional T6 procedure resulted in the softening of SLM AlSi10Mg. This raises the question of the validity of conventional heat treatments when it comes to SLM materials, and what would be the effect of these heat treatments on the overall mechanical behaviour. This is the main focus of the research detailed in this paper.

Research to date has focussed on either the micro- or the macro-scopic mechanical properties of SLM material, hardness, strength, etc., while little work has examined the nano-scale properties, such as nano-hardness. The advantage of using nanoindentation is the very small indentation area and depth of penetration, which are helpful in characterising the local mechanical properties of materials with very fine microstructure, such as SLM AlSi10Mg [12,18]. This paper investigates the various mechanical properties of SLM AlSi10Mg at the nano-, micro-, and macroscopic levels. The sub-micron level is represented by the nano-hardness, determined using nanoindentation. To evaluate the strength of the material at the microscopic level, the micro-hardness is measured. Tensile and compressive tests are conducted to reflect the behaviour of the material at the macroscopic level. In this work, the effect of a conventional T6-like procedure on the microstructure and mechanical behaviour at various scales was studied.

2. Materials and methods

AlSi10Mg powder supplied by LPW Technology was used to produce near fully dense samples (99.94% relative density) for the various mechanical tests in this study. The samples were fabricated using a Renishaw AM250 SLM machine equipped with a 200 W Yb-Fibre laser. The process parameters were 200 W laser power, a laser scan speed of approximately 570 mm/s (achieved by using 80 μm point distance and 140 μs exposure time), 130 μm hatch spacing, 25 μm layer thickness, and a checkerboard scan strategy (also known as island scanning strategy [18]). Cubic samples ($5 \times 5 \times 5$ mm) were produced for nano and micro-hardness tests. Standard dog-bone shaped tensile specimens, following ASTM standard E8/E8M [28], were manufactured with 45 mm gauge length and 9 mm gauge diameter. Standard cylindrical compression test specimens, following ASTM standard E9 [29], were fabricated then machined by turning to 60 mm in height and a 20 mm diameter to ensure the sample had flat parallel ends. Half the samples used in this study were heat-treated following a T6-like procedure by solution heat treatment (SHT) for 1 h at 520 °C followed by artificial ageing (AA) for 6 h at 160 °C [27] before testing. The storage time between quenching the samples and starting the ageing process was kept to a minimum ($\sim$0.5 – 1 h).

A MicroMaterials LTD Nanotest NTX Platform3 nanoindenter was used to measure the nano-hardness and indentation modulus of the samples. A Berkovich tip was used for indentation, with the indenter tip shape factor taken into account in the analysis as well as the thermal drift pre- and post-indentation. Tests were performed in accordance with ASTM standard E2546 [30] in a load-controlled mode. The maximum indentation load was set to 7.5 mN and the horizontal (X) and vertical (Y) spacing between adjacent indentations were 10 μm and 15 μm, respectively. The micro-hardness of the samples was measured using a Vickers indenter, applying a load of 3 N and averaging over 10 indentations per sample. The as-built and heat-treated samples were cross-sectioned, polished, and etched using Keller's reagent [31] to reveal the microstructure. A Nikon Eclipse LV100 ND optical microscope was used to image the microstructure. Monotonic uniaxial tension tests were conducted at room temperature using an Instron 5581 universal testing machine equipped with a 50 kN load cell. The tests were carried out in accordance with ASTM standard E8/E8M [28]. The extension rate was 0.5 mm/min, providing a strain rate of 1.8×10^{-4} s^{-1}. A random spatter pattern was applied to the surface of the tensile samples using white and black spray paints in order to aid strain measurement using a video gauge. A Philips XL30 scanning electron microscope (SEM) with a secondary electron detector operating at 20 kV served to examine the fracture surfaces of the samples after tensile tests. The fracture surfaces were also cross-sectioned along the normal plane, polished, and etched to determine the fracture mode and investigate the microstructure in the fractured region. An energy dispersive X-ray (EDX) detector attached to the SEM served to analyse the chemical composition distribution in the fractured region. Uniaxial compression tests were conducted at room temperature using an Instron 5985 universal testing machine equipped with a 250 kN load cell. This test was conducted following ASTM standard E9 [29]. The compression was applied at 0.3 mm/min, resulting in a strain rate of 8.3×10^{-5} s^{-1} and the test was stopped when the load reached 230 kN. Strain data was collected using a linear variable differential transformer (LVDT) because the video gauge was unsuitable for these tests as the samples barrelled sending the pattern out of focus so that the video gauge lost track of the traced spatter pattern.

The results presented in this study are produced from a number of replicates per experiment. Therefore, the reported average values are quoted with standard error. The standard error is calculated by dividing the standard deviation by the square root of the number of readings being averaged.