MECHANICAL PROPERTIES OF SELECTIVE LASER MELTED AlSi10Mg: NANO, MICRO, AND MACRO PROPERTIES

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Abstract

The selective laser melting (SLM) of aluminium alloys is of great current interest at both the industrial and research levels. Aluminium poses a challenge to SLM compared with other candidate materials, such as titanium alloys, stainless steels, and nickel-based alloys, because of its high thermal diffusivity and low infrared absorptivity and tendency to result in relatively porous parts. However, recent studies have reported the successful production of dense AlSi10Mg parts using SLM. In this study, we report on the nano, micro, and macroscopic mechanical properties of dense AlSi10Mg samples fabricated by SLM. Nanoindentation revealed the hardness profile across individual melt pools building up the parts to be uniform. This is due to the fine microstructure and uniform chemical elements distribution developed during the process due to rapid solidification. Micro-hardness testing showed anisotropy in properties according to the build orientation driven by the texture produced during solidification. Lastly, the tensile and compressive behaviours of the parts were examined showing high strength under both loading conditions as well as adequate amounts of strain. These superior mechanical properties compared to those achieved via conventional manufacturing promote SLM as promising for several applications.

Introduction

Additive manufacturing (AM) technologies, such as selective laser melting (SLM), are currently attracting the attention of researchers and industrial sectors. These technologies are generally utilised to manufacture complex and customised structures that cannot be achieved cost effectively using conventional manufacturing. SLM is a process to fabricate parts from loose powder with the potential to achieve savings in resources, time, and energy. Light-weighting using SLM through topology optimisation [1, 2] or the use of latticed structures [3, 4] to replace bulk solid materials is appealing for various applications to increase functionality and reduce operating costs. The process is commonly used with engineering materials such as titanium alloys [5-8], stainless steels [9-11], nickel-based alloys [12-14], and aluminium alloys [15-20]. Aluminium alloys are widely used in a number of industrial sectors including the medical [8], automotive, and aerospace industries [21]. Processing aluminium alloys by SLM is not as straightforward as with the other candidate materials because of its combination of physical properties. Aluminium has high reflectivity and thermal conductivity that complicate processing and contribute to promoting porosity in the produced parts. This problem requires the use of high laser powers [22], multiple scans per layer to remedy the defects [15], and running prolonged studies in pursuit of finding the best combination of parameters.

The industrial interest in SLM parts from Al alloys imposes the question of whether these parts will be reliable in terms of mechanical properties. From a metallurgical perspective, SLM of Al alloys produces a characteristically fine microstructure [19] developed as a consequence of the fast rates of solidification. This might influence the mechanical properties when compared with the coarse-grained material produced via conventional manufacturing processes. The mechanical properties of SLM parts are affected by several factors, such as the build orientation [16, 23, 24], pre-heating of the build platform [25, 26], and the energy density delivered to the material during processing [26]. The tensile behaviour [16, 26-28] and micro-hardness [24, 27] of SLM Al parts with different degrees of porosity have been previously investigated showing improved strength for the SLM material when compared to the conventionally processed in addition to reduced strength with increased porosity. The compressive behaviour of SLM Al parts has mainly so far focussed on latticed structures [4] rather than solid parts.

This paper reports on the nano, micro, and macro mechanical properties of SLM AlSi10Mg. The nano level is represented by the nano-hardness, determined using nanoindentation. The micro-hardness is measured to represent the micro-behaviour. In addition, tensile and compressive tests are performed to evaluate the mechanical behaviour of the material at the macroscopic level. Considering the different levels of mechanical properties for selectively laser melted Al is new and this work aims at providing a comprehensive understanding of the mechanical behaviour that will beneficial for the development of prediction and simulation models.

Experimental work

AlSi10Mg powder supplied by LPW Technology (UK) was processed using a Renishaw (UK) AM250 SLM machine equipped with a 200 W Yb-Fibre laser to produce test samples for this study. The processing parameters are shown in Table 1. Cubic test samples with a 5 mm side length were fabricated to be used in hardness tests (nano and micro-hardness). To reveal the microstructure the samples were cross-sectioned, polished, and etched using Keller's reagent [29]. A Nanotest^{TM} NTX Platform 3 nanoindenter (MicroMaterials LTD, UK) was used to measure the nano-hardness of the samples using a Berkovich indenter following ASTM standard E2546-07[30] in load control mode (maximum load = 7.5 mN). The indenter tip shape was accounted for in the analysis as well as the thermal drift pre- and post-indentation. A Vickers hardness tester was used to measure the micro-hardness, applying a load of 3 N. Ten indentations per sample were conducted to obtain an average value.

Table 1: SLM processing parameters used to produce test samples.

Laser power (W)	Point distance (µm)	Exposure time (µs)	Hatch spacing (µm)	Layer thickness (µm)	Scan strategy
200	80	140	130	25	checkerboard

Standard dog-bone shaped tensile test specimens were manufactured with a gauge length and diameter of 45 mm and 9 mm, respectively (see Figure 1). These samples were tested using an Instron 5581 universal testing machine following ASTM standard E8/E8M [31] with an extension rate of 0.5 mm/min. The displacement data were collected by a video gauge tracing a random spatter pattern on the surface of the sample formed using white and black spray paints. The fracture surfaces were examined using a Philips XL30 scanning electron microscope (SEM). Standard cylindrical compression test specimens were built and machined down to have a 60:20 height-to-diameter ratio (see Figure 2). Compression tests were conducted using an Instron 5985 universal testing machine following ASTM standard E9 [32] with an extension rate of 0.3 mm/min. Strain data was collected using a linear variable differential transformer LVDT between the crossheads.

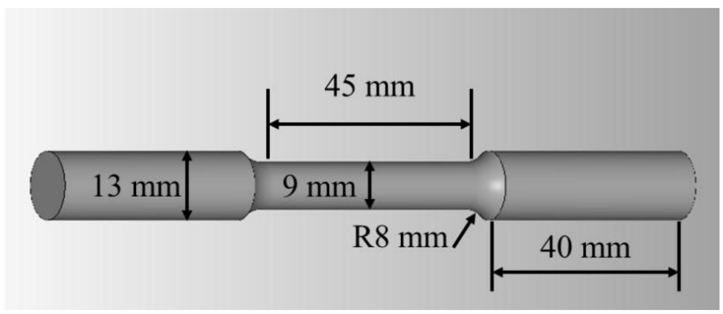

Figure 1: Tensile test specimen dimensions.

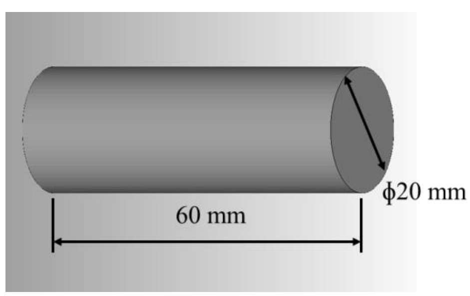

Figure 2: Compression test specimen dimensions.

Results & Discussion

The average nano-hardness of the SLM material was 1.82 GPa (± 0.01 standard error) as determined by indentations on the plane parallel to the build direction. No spatial variation was observed within an array of 104 indentations over an area of 130 µm × 120 µm, i.e. there is a uniform hardness profile. This uniform nano-hardness is attributed to the fine microstructure and uniform distribution of the alloying elements. The size of a nano-indent is larger than the average grain size of SLM AlSi10Mg, as demonstrated in Figure 3, where every indentation encompasses a number of few grains. Fast solidification during SLM produced a fine microstructure with continuous Si segregation at the grain boundaries of the α-Al grains. This is a typical microstructure for SLM Al-Si alloys [28]. This means that SLM produces parts with a homogenous distribution of the different alloying elements, which in its turn leads to enhanced mechanical properties in terms of showing no spatial variation in the local mechanical properties.

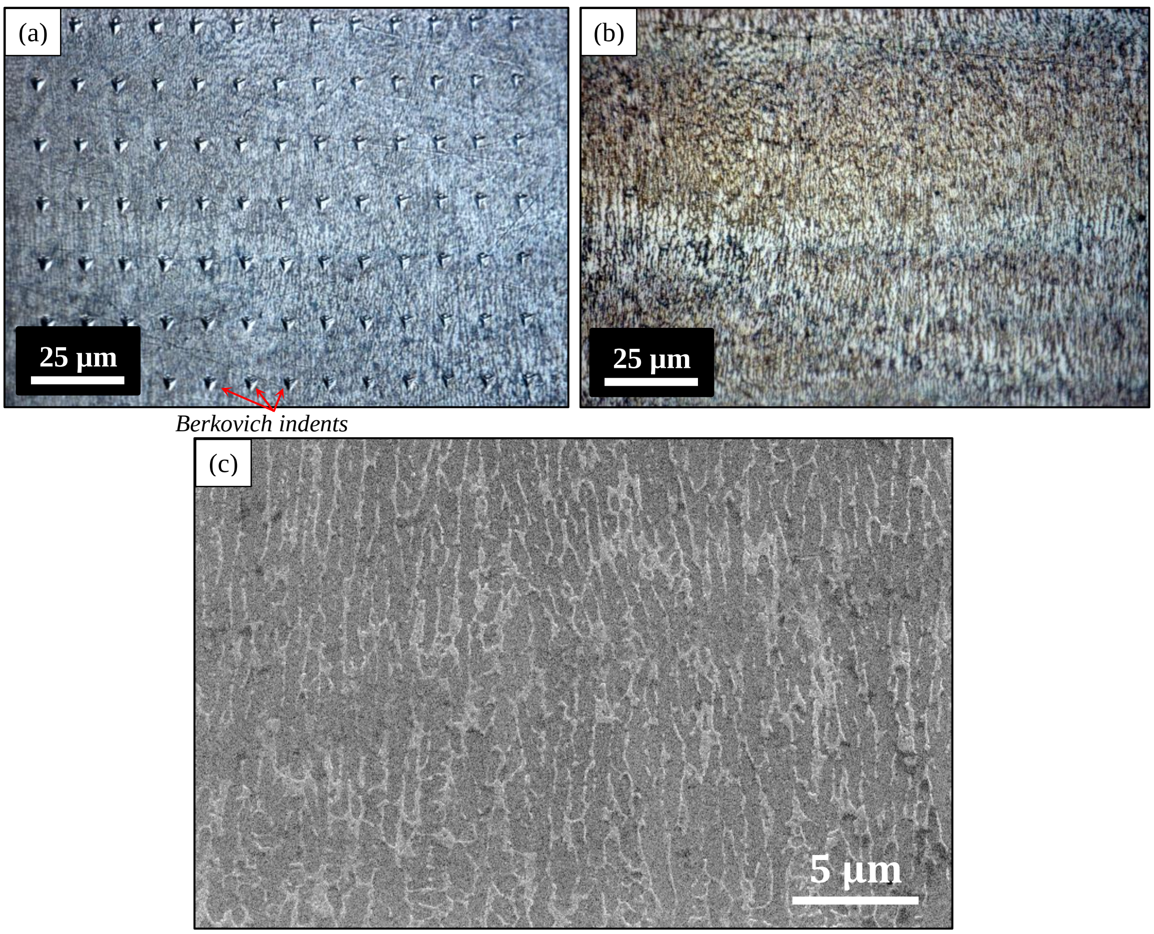

Figure 3: Micrographs showing (a) the array of indentations formed by a Berkovich tip using nanoindentation on the polished surface of SLM AlSi10Mg, (b) the indented region after etching by Keller's reagent, and (c) higher magnification of the microstructure showing the grain size to be smaller than the nano-indent size.

The micro-hardness was (109.7 ± 0.9) HV for indentations on the plane parallel to the build direction. This micro-hardness is higher than the die cast counterpart by almost 10% [24]. The plane perpendicular to the build direction showed an average micro-hardness of (99.07 ± 2) HV. The difference in hardness between the two planes indicates anisotropy in the mechanical properties. Anisotropy in the mechanical properties of SLM parts from Al alloys has been previously reported by [16, 24] and attributed to the layer-by-layer approach and the grain structure and texture developed as a result of the thermal gradient.

The engineering stress-strain curve in Figure 4 shows that the samples behaved in a relatively brittle fashion, as demonstrated by the low elongation to failure and the high ultimate tensile strength (UTS). The tensile strength of the SLM AlSi10Mg supersedes that of the A360 die cast material (~320 MPa UTS and 175 MPa yield strength [33]) but the ductility of the SLM material is less than that of the die-cast A360 (~3.0% [33]), which is an alloy with a fairly comparable composition to AlSi10Mg. The contributors to strengthening the SLM material are (1) grain size reduction developed by rapid solidification, (2) solid solution strengthening, and (3) dislocation strengthening.

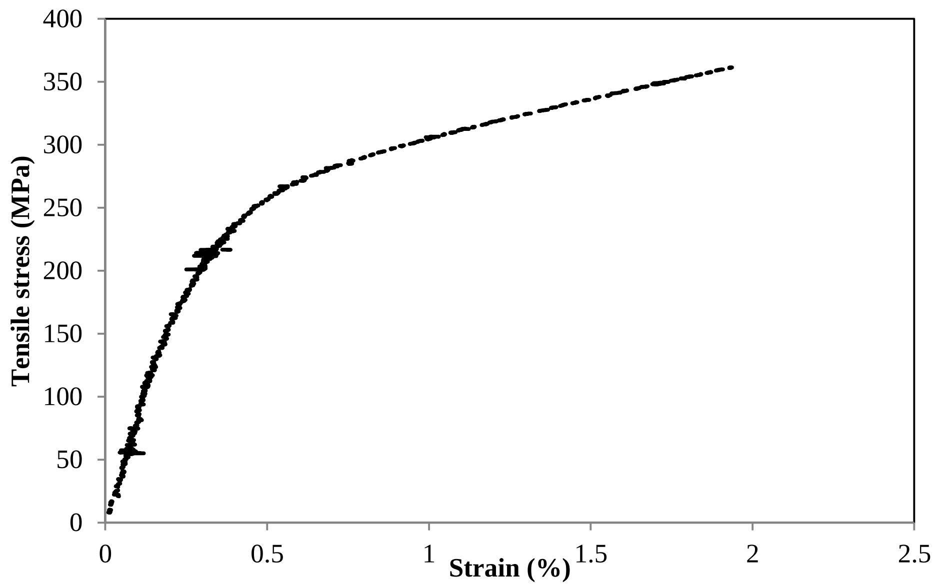

Figure 4: Engineering tensile stress-strain curve demonstrating the behaviour of SLM AlSi10Mg.

Failure in all the observed samples started at a surface or sub-surface defect (see Figure 5) and propagated circumferentially until the load bearing area became so small that fast propagation occurred on a plane inclined to the fracture surface by 45º (shear lip). This scenario is demonstrated in the cross-sectioned fracture surface in Figure 6. The fracture surface is shell shaped, i.e. the removed material is in the shape of a series of adjacent crescents. This suggests that the crack propagates along the boundaries between melt pools, i.e. failure through de-cohesion from one layer to another. This is because the crack follows the softer regions in the material. The melt pool boundary has a coarser microstructure compared to its core, which indicates a reduction in the grain boundary area meaning less Si segregations at these regions [34].

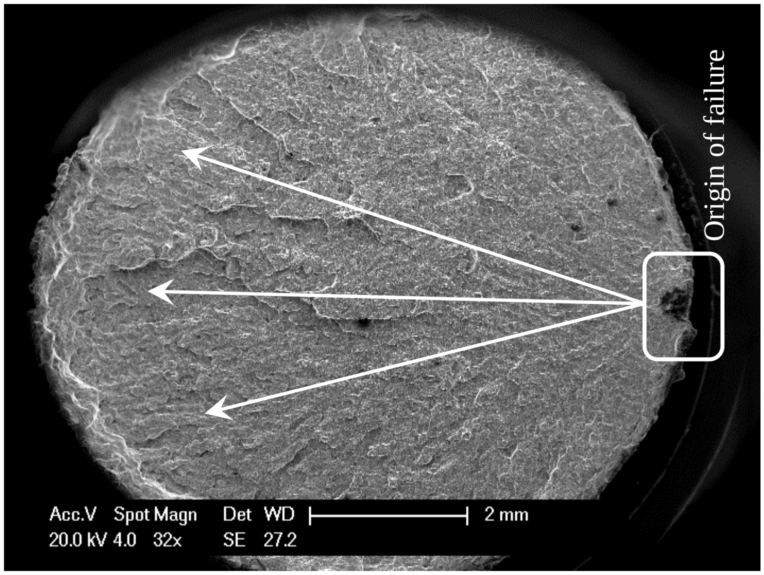

Figure 5: The overall fracture surface of a tensile sample with the origin of failure highlighted along with the direction of crack propagation pointed out by arrows.

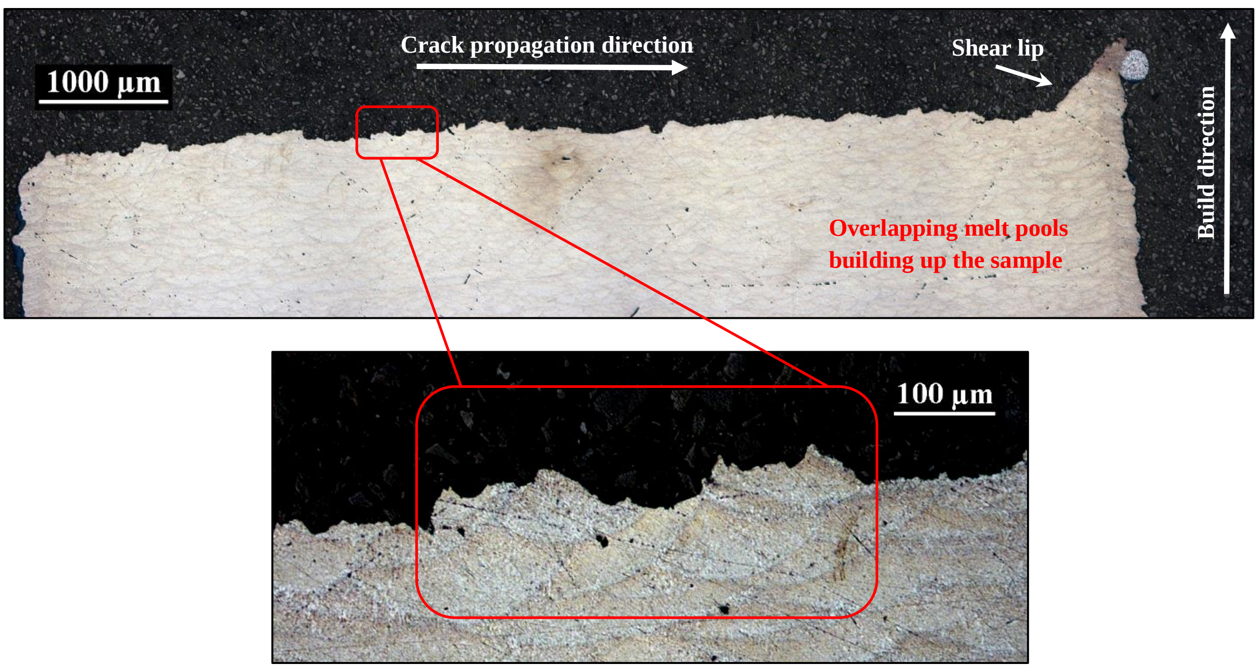

Figure 6: Cross-sectional view of the fracture surface of a tensile sample demonstrating crack propagation along melt pool boundaries.

The compressive behaviour is demonstrated by the representative curve in Figure 7. The samples did not fracture under compressive loading, but rather deformed by buckling until the load reached the maximum capability of the test rig, when the test was stopped. The compressive strain at failure in this case cannot be quantified because failure was not observed.

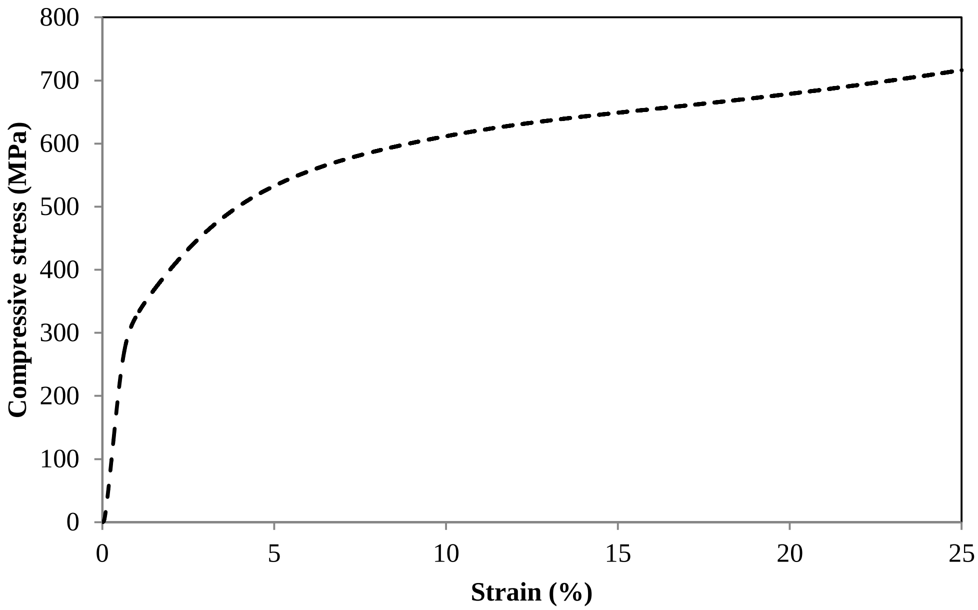

Figure 7: Representative curve for the compressive behaviour of SLM AlSi10Mg.

Summary & Conclusions

The SLM material showed uniform nano-hardness because of the very fine microstructure and good distribution of Si segregated at the grain boundaries of the α-Al. The micro-hardness was better than the die cast equivalents but the SLM part showed evidence of anisotropy in which the hardness along the build direction was higher than the perpendicular one. Similarly, the tensile strength was higher than the die cast counterpart but with poorer ductility. The compressive strength of the SLM AlSi10Mg was also determined and the material performed in a ductile manner, i.e. samples didn't fracture under compressive loading. The reported results in the study are important as they pave the way towards acquiring a comprehensive understanding of the mechanical behaviour of the SLM material at the multiple scales. The presence of a complete data set of the mechanical properties of the selectively laser melted material, such as the one presented here considering the multi-scale mechanical properties, aids in the development of prediction and simulation models. Moreover, this study, to the authors' knowledge, is the first to report on the compressive properties of solid selectively laser melted Al alloys since the work found in the literature is mainly restricted to the compressive behaviour of latticed structures. This work will be followed by research incorporating the effect of various heat treatments on the mechanical properties since the response of SLM Al material to heat treatments, in terms of microstructure evolution and hardness, was previously reported to be different from conventionally manufactured materials [34].

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