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Improving the fatigue behaviour of a selectively laser melted aluminium alloy: Influence of heat treatment and surface quality

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ABSTRACT

Selective laser melting (SLM) is being widely utilised to fabricate intricate structures used in various industries. Widening the range of applications that can benefit from such promising technology requires validating SLM parts in load bearing applications. Recent studies have mainly focussed on static loading, with minor attention to cyclic loading despite its vital importance in many applications. In this work, the fatigue performance of SLM AlSi10Mg was investigated considering the effects of surface quality and heat treatment. Compared to heat treatment, machining the samples played a minor role in improving the fatigue behaviour. This is potentially attractive to industries interested in latticed structures and topology-optimised parts where post-processing machining is not feasible. The characteristically fine microstructure in the as-built samples provided good fatigue crack propagation resistance but none of them survived nominal fatigue life of 3×10^7 cycles within the maximum stress range of 63–220 MPa. A specially-tailored heat treatment increased the material's ductility, significantly improving its fatigue performance. At 94 MPa, the heat-treated samples survived beyond the nominal fatigue life, outperforming the reference cast material. The combined effect of machining and heat treatment yielded parts with far superior fatigue properties, promoting the material for a wider range of applications.

1. Introduction

Additive manufacturing (AM) via selective laser melting (SLM) enables the fabrication of geometrically complex structures, providing various industrial sectors with a range of opportunities, such as lightweighting and added functionality [1,2]. Drastic weight reduction can be achieved by several methods, such as topology optimisation [3,4] or replacing a bulk of solid material with latticed structures [5,6]. AM has the potential to fulfil demands for cost and design-to-manufacturing time reduction through saving on raw materials and replacing a series of production processes with a single step process. AM, also, promotes the possibility of producing cost-effective customised products [7,8]. Parts produced using AM are already widely used in various fields, such as the medical [9], automotive, and aerospace industries [7]. Fabricating load bearing parts using SLM, such as automotive power trains, turbine components [10], or aerospace components [11], is becoming more commonplace, therefore studying their mechanical performance is gaining further attention to cope with the widely expanding popularity for the process [12] and confirm its credibility. Recent studies have mainly considered the static tensile properties of the parts [10,13,14], with less attention so far to fatigue performance, as stated by [15]. Fatigue behaviour of parts is one of the important properties to be considered when evaluating a material for application in industry.

SLM parts can suffer from cracks [16], pores [17], poor surface roughness, and high residual stresses [18] arising from the high energy density {energy density = laser power / (scan speed ∗ hatch spacing ∗ layer thickness) [19]} induced by the process and subsequent fast solidification [20,21] and high thermal gradients. SLM materials also have distinctive microstructures [22] when compared to conventionally processed materials. All these features affect the mechanical properties of SLM parts and differentiate them from those manufactured by conventional processes [13]. Although the porosity of SLM parts, processed with optimised parameters, does not drastically reduce the load bearing area and might not be therefore sufficient to reduce the stiffness of the material in load bearing applications [13], this is not the case for fatigue performance [21], which is strongly affected by the presence of pores [23]. The probability of failure under cyclic loading increases as the fraction or size of defects increases since fatigue cracks nucleate at these defects [15,20,24]. The sensitivity of fatigue properties to surface defects, accentuated by the poor surface roughness, has been widely reported for SLM titanium alloys [20,25,26] and stainless steel [27]. Brandl et al. [15] investigated the fatigue behaviour of SLM AlSi10Mg samples with machined surfaces. Mower and Long [28], on the other hand, tested SLM AlSi10Mg samples with as-built and polished surfaces and reported a poorer fatigue performance in both cases, compared to the results of

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Brandl et al. [15]. It is important to note that these two studies used different SLM systems and processing parameters that can lead to different levels of porosity in the produced samples. Therefore, it cannot be confirmed that the surface quality of SLM AlSi10Mg plays a major role in controlling the fatigue performance.

Several approaches to improve the fatigue behaviour of SLM parts have been reported in the literature. For instance, the fatigue endurance limit can be doubled through reducing the surface roughness for Ti-6Al-4V [9,29]. Siddique et al. [30] and Shiomi et al. [18] agreed that the use of a heated platform (200 °C) or using double scan strategies diminished the residual stresses. Nevertheless, it has been previously reported that heating the platform does not affect the mean fatigue strength of the material but rather reduce the scatter in results [15]. Riemer et al. [27], working on stainless steel, reported stress-relief, through heat treatment or hot isostatic pressing, to yield fatigue properties that were the same as, or even better than those of, conventionally manufactured samples. Edwards and Ramulu [20] recommended peening to induce compressive residual stresses at the surface since their Ti-6Al-4V SLM parts had tensile residual stresses. Post manufacturing heat treatment is a means of reducing the residual stresses in SLM parts. Although heat treating SLM parts is usually guided by the procedures laid out for conventional materials, it is important to note that this might not be generally applicable due to the difference in starting microstructure [21]. The authors of this paper have previously reported [31] an investigation into the heat treatment of SLM AlSi10Mg using a conventional T6 procedure, and observed material softening, rather than the hardening effect that takes place after T6 heat treatment of a conventionally processed AlSi10Mg. They, further, developed an understanding of how to tailor the heat treatment procedure for SLM parts to achieve a particular mechanical response.

AlSi10Mg is commonly used in the automotive industry for its high specific strength [24], in applications where fatigue performance is also critical [32]. Therefore, this paper investigates the fatigue behaviour of SLM AlSi10Mg and determines the effect of the sample's surface quality and heat treatment on the material's performance under cyclic loading. This paper aims to define the importance of the surface quality as a factor influencing the fatigue behaviour of SLM parts made from Al alloys and find an alternative to post process machining that would enhance the fatigue performance. This alternative will further promote the feasibility of using AM processes for light-weighting purposes where a geometrically complex structure needs to be fabricated without the capability of post-process machining as in the case of latticed structures and topology optimised parts.

2. Materials & methods

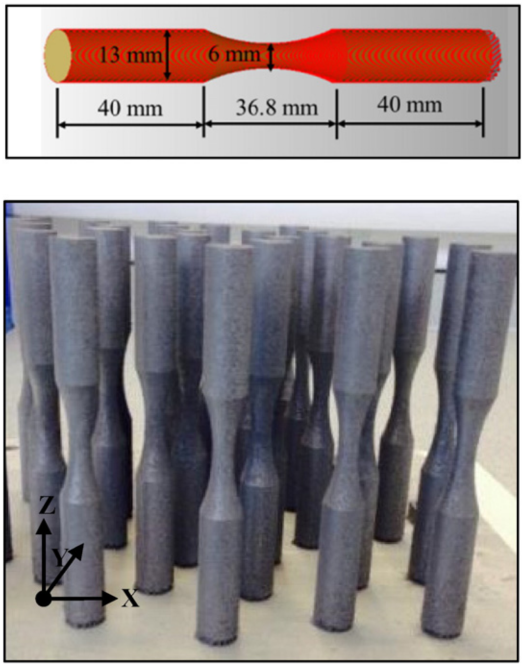

Fig. 1. Fatigue samples fabricated using SLM with the build direction parallel to the Z-axis.

AlSi10Mg powder supplied by LPW Technology was used in this study, the properties of the powder can be found in [17]. A Renishaw AM250 SLM machine was used to fabricate two batches of standard fatigue test specimens with reduced gauge sections (Fig. 1) with continuous radius of curvature between the grip ends, as per ASTM standard E466 [33]. Each batch of samples was made up of 36 samples. The samples had a 6 mm minimum diameter and a 36.8 mm gauge length. The processing parameters employed are shown in Table 1. The layer thickness is the thickness of each layer of powder deposited prior to the laser scan. The scan speed is the speed the laser beam rasters across the powder layer, which is dictated by the point distance and the exposure time at each point. The hatch spacing is the offset between two adjacent scans. The chessboard scan strategy is the same as the island scan strategy described in [22]. The process parameters used were optimised to produce parts with minimal porosity (below 0.5%) and a relatively small layer thickness was used to minimize surface defects and irregularities. The build platform was maintained at 180 °C during processing to minimize residual stresses [30] and scatter in fatigue data [15]. The machine is equipped with a Yb-fibre laser ($\lambda = 1064$ nm) and the spot size of the laser beam focused at the powder bed is 70 μm. The machine processes under argon atmosphere with an oxygen content below 0.09%.

Batch 1 was tested without machining and Batch 2 was machined by turning to reduce the surface roughness; machining allowance was taken into consideration when building the samples by accounting for extra material removal (1 mm in diameter). The surface of the sample before and after machining was imaged using a Hitachi TM3030 scanning electron microscope (SEM), equipped with a backscatter electron detector operating at 15 kV, to determine the effect of machining on the surface quality. Also, a Mitutoyo Surftest SV-600 was used to measure the surface roughness (R_a) of the samples with and without machining. Half the samples in each batch were heat-treated following a conventional T6 procedure. The samples were solution heat treated for 1 h at 520 °C followed by water quenching to room temperature and then aged for 6 h at 160 °C. This was previously shown by the authors [31] to provide the material with increased ductility. As-built and heat-treated samples were cross-sectioned, polished, and etched using Keller's reagent [34] to reveal their microstructures. These were imaged using a Nikon Eclipse LV100 ND optical microscope and a Philips XL30 SEM equipped with a secondary electron detector operating at 20 kV.

Uniaxial fatigue tests were conducted in load-controlled mode following ASTM standard E466 [33]. Before testing, the machined samples were inspected visually using optical microscopy to ensure they were free of abnormalities, such as cracks or undercuts. The specimens were also cleaned with ethanol prior to testing to remove any surface dirt or oils. An Instron 8801 servo-hydraulic fatigue testing machine with a 100 kN load cell was used for the tests. Tests were conducted in air at room temperature (approximately 21 °C and 30% relative humidity). The cyclic loading followed a sine wave with a frequency of 30 Hz. The effect of frequency variation when testing Al alloys for fatigue behaviour is reported to be insignificant [35]. In the axial fatigue loading, the stress

Table 1
Processing parameters using Renishaw AM250 to produce near fully dense fatigue samples.

Laser power	Layer thickness	Scan speed	Hatch spacing	Scan strategy
200 W	25 μm	570 mm/s	80 μm	Chessboard