Fatigue Performance Improvement of AlSi10Mg Manufactured by Selective Laser Melting through Heat Treatment

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ABSTRACT

The quality and performance of the additive manufactured (AM) parts depend on the build orientation. Therefore, in the present work, the rotation bending fatigue (RBF) was tested for two different materials, AlSi10Mg and Al6061. The study aims to identify two different conditions (i.e., room temperature and preheated at 200°C/2hrs) manufactured by the SLM-AlSi10Mg alloy. However, the fatigue performance of the AlSi10Mg alloy showed better results than the Al6061-cast alloys because of the very fine microstructure and fine distribution of the Si phase in the AlSi10Mg SLM parts. These results indicate that most fatigue cracks are initiated by the unmelted defects of the sample surfaces. The SLM building orientation process is the most important for the improvement of fatigue strength. Moreover, the crack propagation mechanism is revealed by fracture analysis. The laser energy density was calculated based on the given process parameter as 150 J/mm³. The highest density achieved was 99.6% (2.660 g/cm³) and obtained defect-free components.

KEYWORDS

Selective Laser Melting (SLM), AlSi10Mg alloy, Fatigue Performance, Failure Analysis.

INTRODUCTION

The AlSi10Mg alloys as a very lightweight material have been extensively studied in the selective laser melting (SLM) process due to their high strength-to-weight ratio and corrosion resistance, as well as high electrical and thermal conductivity, and high ductility [1,2]. AlSi10Mg, along with other aluminium alloys, is typically used for casting thin-walled structures and complex shapes [3]. This is the most popular and widely used aluminium alloy that is also used in additive manufacturing [4]. The conducted a comprehensive study to characterise the properties of SLM-manufactured AlSi10Mg components, including microstructure, high cycle fatigue, and fracture behaviour during as-built and preheated conditions [5]. It was found that the as-built microstructure mainly consists of α-Al cell dendrites and Si particles [6]. This suggests that process parameters (scan speed, laser power, powder deposition, etc.) need to be improved to increase component density (99%) and avoid defects [7]. In recent years, the development of layer additive manufacturing (LAM) technology has made it possible to accurately and efficiently manufacture complex 3D components from metal powder and CAD models [8].

However, due to the highly directional columnar particle structure, the material in manufacture also exhibits obvious anisotropic properties, which can lead to premature failure of AM components during service [9,10]. In addition, AM technology has other drawbacks [11]. These are expected to always be applied in the manufacture of structural parts where various significant defects (part warpage, cracks, lack of fusion (LOF), pores, inclusions, etc.) are not allowed [12]. Defects caused by the AM process adversely affect the fatigue life of AM components, especially when exposed
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to periodic loads [13]. Therefore, it is necessary and indispensable to systematically investigate the mechanism of AM defect generation and the damage behaviour of AM-Al alloy [14]. The considered impact of inherent AM defects, surface roughness, AM process parameters, heat treatment processes, and building orientation on fatigue performance is discussed [15,16]. The various mechanical properties of SLM-manufactured AlSi10Mg are compared to conventional cast Al6061 parts [17]. Due to their extremely fine microstructure and uniform Si distribution, AlSi10Mg parts manufactured with SLM have a high comparison of hardness and fatigue life [18,19]. The SLM test piece exhibits anisotropy in strain results due to the high porosity of the boundary line formed by the Z-aligned fatigue test piece [20,21].

Compared to conventional AM processed alloys, it has higher strength, corrosion resistance, and wear resistance, and its unique hierarchical structure improves component performance, so it is attracting attention [22,23]. In this study, we investigated the fatigue behaviour of AlSi10Mg produced by SLM [24]. The effects of optimal process parameters on fatigue and crack properties were studied [25]. The ultrasonic fatigue test assumed three different load conditions [26,27]. The fracture surface was observed using a scanning electron microscope (SEM), and the roughness of the fracture surface was measured using a three-dimensional (3D) white light interferometer [28,29]. In addition, the fatigue intensity of the samples generated by SLM was assessed in the form of the S-N curve (fatigue life or fatigue strength) using statistical analysis [30]. Several recent studies have been conducted on the AlSi10Mg alloy produced by SLM. The corresponding production parameters have been investigated, the effects of the working environment and installation orientation have been investigated, and the effects of powder parameters on density or porosity have been investigated.

MATERIAL AND METHOD

Material

The AlSi10Mg alloy powder showing composition in table 1 is provided by SLM solution Ltd. and offers a powder particle size range of 20-63 µm from SLM Solution Germany. The provided SLM Solution AlSi10Mg has a density of 2.67 g/cm³. The sample prepared for SLM printing as per the ASTM standard E2948 for cyclic rotating bending fatigue test as shown in figure 1.

Table 1. Chemical composition of AlSi10Mg alloy.

<table>
<thead>
<tr>
<th></th>
<th>Al</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Zn</th>
<th>Ti</th>
<th>Ni</th>
<th>Pb</th>
<th>Sn</th>
<th>Other total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balance</td>
<td>9.00 - 11.00</td>
<td>0.55</td>
<td>0.45</td>
<td>0.20 - 0.45</td>
<td>0.10</td>
<td>0.15</td>
<td>0.05</td>
<td>0.05</td>
<td>0.15</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 1. a) Powder particle size distribution and b) wear specimen.
SLM Process

The fatigue test circular-bar rod specimens were built by an SLM M280 (M280 2.0) system equipped with a 280×280×365 mm building platform and an up to 400 watt continuous Yb: YAG fiber laser as shown in figure 2. A beam focus diameter of 80 to 115 μm and a scan speed of up to 10 m/s, an automatic AlSi10Mg powder spreading on the build platform device, an inert argon gas protection system, and a computer-based system for control of the process. The used laser power is P = 225 W, scan speed v = 500 mm/s, the hatching spacing h = 100 μm, the layer thickness t = 30 μm, build platform temperature considered as 150°C and wear samples fabricated in the horizontal direction as shown in figure 3. The laser energy volume was calculated by $E = \frac{P}{v \times h \times t}$ [7] (eq.1), and the value of laser energy density was 150 J/mm³. The SLM production was performed in an inert argon atmosphere to avoid the pick-up of interstitial oxygen (lower than 0.2%).

![SLM schematic diagram and printing process based on process parameter.](image1)

**Figure 2.** (a & b) SLM schematic diagram and printing process based on process parameter.

![Layout of specimen on SLM 280 build platform and samples obtained by taguchi L9 OA.](image2)

**Figure 3.** Layout of specimen on SLM 280 build platform and samples obtained by taguchi L9 OA.
RESULTS AND DISCUSSION

In this research work, we conducted fatigue experiment tests at two different conditions, i.e., room temperature and preheated at 200°C/2hrs. The additive simulation layer-by-layer was also done before the SLM printing process and observed thermal gradient.

Additive simulation

The additive layer-by-layer simulation is the most important part of SLM printing because it saves time, material, and cost. Based on the design of experiment parameters, additive simulation was done and the results are as follows: displacement of 0.7689 mm, plastic strain of 0.38, temperature distribution in the SLM printing process of 451.2K and von mises stress of 236.6 MPa as shown in figure 4.

Dynamic performance of AM part-Fatigue testing

Dynamic bending fatigue performance is more important for applied dynamic load on aerospace components. It is well known that the fatigue strength of AlSi10Mg alloys depends on metallurgical defects and porosity effects in oxide layer films. The fatigue performance was conducted in a fully reversed with rotating bending mode. The conducted a fatigue tests at room temperature on the motor with a driven shaft rotating beam machine. The machine components are; flexible bearing, weight hanger assembly, bearing spindle (shaft), bearing and its housing assembly, chuck, digital counter, AC electric Motor Specimen as shown in figure 5.

Figure 4. a) Thermal simulations of displacement and b) SLM printing temperatures used in printing process.
The AlSi10Mg material was used in the experimental work to make a prediction of the fatigue life cycle. The prediction of fatigue life requires the experimental measurement of localised loads in kg or N. A variety of methods may be used to predict the fatigue life by applying weights and measuring with respect to time. Experimental measurements are made to determine the minimum and maximum values of the load and time to repetition of the cycle. The predict fatigue damage for structural components subjected to variable loading conditions. The first, simplest, and most widely used damage model is linear damage. Fatigue is a localised damage process of a component produced by cyclic loading. The results of the cumulative process consisting of crack initiation, propagation and final fracture of a component, during cyclic loading may be localised plastic deformation may occur at the highest stress range. The plastic deformation induces permanent damage to the component and a crack develops. The increasing number of loading cycles, the length of the crack (damage), increases. After a certain number of cycles, the component fails or separates.

The fatigue process involves the following stages: crack nucleation, short crack growth, long growth, and final fracture as shown in figure 6. A typical fatigue test piece has three areas: a test section and two grip clamps or ends. The grip hold ends are designed for load transfer from the test machine hold to the test section and can be identical, especially in rotary bending fatigue tests, to eliminate any stress concentrations in the transition from the grip ends to the test region; broad, smoothly blended radii are used. The design and type of test piece used depend on the fatigue tester used and the purpose of the fatigue test. To avoid damage to the clamp ends and sample failure, the test section of the specimen should be sized to take the fatigue load capacity with a reduced cross section. Table 2 and figure 7 shows the results of a test performed on all specimens and obtained as a process parameter at a specific constant load (i.e., stress amplitudes 116.11, 145.14 and 145.14 MPa). The experimental test was done every load with an average of 3 specimens at two different conditions: room temperature and preheated (200°C/2hrs). The calculation of fatigue life cycles as following:

- The motor rpm is 2880, 1 minute is equal to 2880 rev (i.e., 1 sec = \( \frac{2880}{60} = 48 \) rps),
- The number of cycles is equal to time taken \((s) \times 48 \) rps and
- The prediction of fatigue strength calculation: Length of the shaft \((L)\) is 490 mm, Diameter of the shaft \((d)\) is 15 mm, and applied load for fatigue test is 8, 10 and 12 kg,
  - Weight \((W)\) = 8 × 9.81 = 78.48 N,
  - Bending moment \((M)\) = \(W \times L\)…. (eq.2) \[29\] = 38455.2 N-mm and
  - Bending stress \((\sigma_b)\) = \(\frac{32M}{\pi d^3}\) ….. (eq.3) \[29\] = 145.14 MPa.
  And similarly applied for 10 kg = 145.14 MPa and 12 kg = 174.17 MPa.
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Figure 6. After experiment 3D printed of AlSi10Mg samples.

Table 2. After experimental test conducted of fatigue test results

<table>
<thead>
<tr>
<th>Load in MPa</th>
<th>As Built Al 6061</th>
<th>Preheated (200°C/2hrs) Al 6061</th>
<th>As Built 3D AlSi10Mg</th>
<th>Preheated (200°C/2hrs) AlSi10Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>116.11</td>
<td>1.44×10⁴</td>
<td>1.58×10⁴</td>
<td>1.87×10⁴</td>
<td>2.16×10⁴</td>
</tr>
<tr>
<td>145.14</td>
<td>8.3×10³</td>
<td>1.0×10⁴</td>
<td>1.2×10⁴</td>
<td>1.46×10⁴</td>
</tr>
<tr>
<td>174.17</td>
<td>4.3×10³</td>
<td>5.7×10³</td>
<td>7.2×10³</td>
<td>9.2×10⁴</td>
</tr>
</tbody>
</table>
After completing experimental tests, the comparison of Al6061 and SLM-ALSi10Mg alloy fatigue performance showed better results than the Al6061-cast alloys because of the very fine microstructure and fine distribution of the Si phase in the AlSi10Mg SLM parts. The EDX test also concluded that the powder particle distribution is AlSi10Mg. The weight of Al is 90.95 and Si is 9.05. The comparison of fatigue performance % wise is shown in table 3.

Table 3. Comparison of results of casting Al6061 and literature survey (fatigue life cycle)

<table>
<thead>
<tr>
<th>Comparison of work</th>
<th>Increment Fatigue cycle in (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casting Material</td>
<td>20 %</td>
</tr>
<tr>
<td>Literature survey [26]</td>
<td>5 %</td>
</tr>
</tbody>
</table>

During fatigue testing, the test specimen is subjected to alternating loads until to failure. The loads applied to the specimen are defined by either a constant stress range ($S_r$) or a constant stress amplitude ($S_a$).

- The stress range ($S_r$) defined ratio of different between the maximum stress ($S_{max}$) and minimum stress ($S_{min}$)
  \[ S_r = S_{max} - S_{min} \quad \text{(eq.4) [30]} \]
  \[ = 174.17 - 116.11 = 58.06 \text{ MPa} \]
- Stress amplitude is equal to one half of stress range
  \[ S_a = S_r/2 = S_{max} - S_{min}/2 \quad \text{(eq.5) [30]} \]
  \[ = 58.06/2 = 29.03 \text{ MPa} \]
- For fatigue analysis to consider tensile stresses positive and compressive stresses negative. The no. of cycle to failure is the fatigue life ($N_f$) and each cycle is equal to two reversal ($2N_i$).
- The most of time S-N fatigue testing is conducted using fully reversed loading. Fully reversed indicated to mean stress
  \[ \text{Mean stress} (S_m) = S_{max} + S_{min}/2 \quad \text{(eq.6) [30]} \]
  \[ = 145.14 \text{ MPa.} \]
- Two parameters, the stress ratio (R) and the stress amplitude ratio (A). the stress ration is defined as the ratio of minimum stress ($S_{min}$) to maximum stress ($S_{max}$)
  \[ R = S_{min} / S_{max} \quad \text{(eq.7) [30]} \]
  \[ = 0.66 \]
The amplitude ratio is the ratio of the stress amplitude to mean stress
\[ A = \frac{S_a}{S_m} = 1 - R / (1 + R) \text{ (eq. 8) [30]} \]
\[ = 1 - 0.66 / (1 + 0.66) = 0.204 \]

All the stress amplitudes, maximum stress, minimum stress, and stress range are plotted in cycle stress as shown in figure 8, and the fatigue is calculated based on the fatigue limit as shown in figure 9.

**Figure 8.** Symbols used with cyclic stresses and cycles.

The calculation of fatigue limit as \[ S_e = S_{be} \times C_L \times C_S \times C_D \times C_R \text{ (eq. 9) [30]} \]

Where,
- \( S_e \) = Fatigue limit
- \( S_{be} \) = Bending fatigue limit \( (S_{be}/S_u = 0.5) \)
- \( S_u \) = Ultimate tensile stress
- \( C_L \) = Type of loading (Bending 1.0 [book])
- \( C_S \) = Surface finish (UTS=342 MPa i.e., 0.7 [book])
- \( C_D \) = Specimen size \( (d<8 \text{ mm i.e., } 0.7 \text{ [book]}) \)
- \( C_R \) = Reliability level \( (S_{1000}/\text{no. of cycle}) \)

Therefore, \( S_e = 171 \times 1.0 \times 0.7 \times 0.7 \times 0.99 = 82.95 \text{ MPa} \)

**Figure 9.** Modified S-N curve for smooth components made of AlSi10Mg.
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Fracture Analysis

The scanning election microscope (SEM) was used to examine the fracture surface of the damaged test piece in order to obtain detailed information on the start of cracks. The fracture surface can be roughly divided into three zones based on the characteristics of SEM, as shown in Figures 10. Smooth zones in the SEM image are formed by crack initiation and slow propagation and are called initiation zones. In general, the starting zone includes the initial defect where the crack begins and the zone caused by the slow propagation of the crack. For surface starting, the start zone tends to be a semicircle. In contrast, if the crack starts from the inside, it will be a circle. All printed parts were horizontal building orientations, and the results were compared to the 90° building orientations in the literature review [24]. The size of the fisheye of a specimen built at 90° is usually much larger than that of a specimen built at 0° due to the difference in the structure of the molten pool.

For 0° built specimens, cracks propagate through the build layer as shown in figure 10a. The crack must cross the weld pool. The microstructure is very fine and occupies most of the melt pool, which is most likely to crack in the melt zone. The temperature near the center of the molten pool is high, and the structure is relatively fine. In a sample built at 90°, however, the cracks propagate in the same layer as shown in Figure 10b. This indicates that the fracture surface contains a large number of gas holes and that fatigue cracks are due to the holes on or under the surface. The inner surface of the pores is smooth (figure 10d), which is characteristic of gas pores. It is clear that the presence of these pores directly or indirectly promoted the formation and propagation of cracks. Fracture surfaces are generally similar at different porosity levels (figure 10c), but the propagation zones of low porosity samples tend to be smaller parts of the fracture surface. At the same porosity level, it was found that the test piece with higher fatigue stress had a smaller propagation zone. In addition, the forced rupture area has no dents, indicating low ductility.
EDX for Fracture Phase Composition

As shown in figure 11, the XRD of SLM-AlSi10Mg detected the typical α-Al phase and eutectic Si in SLM-AlSi10Mg. It is concluded that due to the rapid cooling during the SLM process, Si becomes supersaturated and precipitates in the Al matrix. In addition, the Al peak of SLM-AlSi10Mg has a stronger intensity in the horizontal direction. For cubic AlSi10Mg, the crystal orientation is parallel to the major axis of the columnar particles and has the lowest atomic packing density, which is the preferred crystal growth direction. The different textures of SLM-AlSi10Mg along the XY direction demonstrate that columnar Al particles grow along crystal facets due to preferential solidification along the crystal orientation. Several β-Al5FeSi phases are formed, and the intensity of the Si peak is very weak. Harmful Fe-containing intermetallic compounds tend to form during equilibrium enhancement at slower cooling rates. The weight of Al is 90.95 and Si is 9.05 from the EDX experiment.

Figure 10. Fracture regions of AlSi10Mg (a) propagation, (b) pores (c) porosity and (d) dimples and Si particles.

Figure 11. SEM AND EDX for fracture sample of AlSi10Mg.
Hardness and density

The hardness test was conducted as per ASTM E384 and also the archimedes test, as per ASTM standard SI 10. The Vickers hardness and density results are based on the optimal process parameters. The hardness and mechanical property values are mainly dependent on the microstructure of pores, cracks, and porosity with thermal deviation. The results of microhardness tests under three different areas under an applied load of 1000 grams with a holding time of 10 seconds showed that the value of hardness was 126±5 [13]. The theoretical density of AlSi10Mg alloy powder ($\rho_t$) is 2.67 g/cm$^3$ and, after SLM, manufactured parts have the highest density of 2.66 (99.6%) g/cm$^3$.

CONCLUSION

In this research, the cyclic rotating bending fatigue performance of SLM-AlSi10Mg results was compared with as-cast Al6061 results and three different loads were applied. The conducted experimental tests were at two different conditions (i.e., room temperature and preheated at 200°C).

- The laser density was calculated at 150 J/mm$^3$ (laser power of 225 watts, scan speed of 500 mm/s, hatching distance of 100 µm and layer thickness of 30 µm).
- The highest fatigue life cycles were achieved at preheated (200°C/2hrs) conditions at 116.11 MPa of $2.16 \times 10^4$, 145.14 MPa of $1.46 \times 10^4$ and 174.17 MPa of $9.2 \times 10^3$. The hardness is a 3D printed hardness of 126±5 and a preheated (200°C/2hrs) hardness of 129±5. The highest density achieved was 99.6% (2.660 g/cm$^3$) and obtained defect-free components.
- The fatigue performance of the AlSi10Mg alloy showed better results than the Al 6061-cast alloys because of the very fine microstructure and fine distribution of the Si phase in the AlSi10Mg SLM parts.
- These results indicate that most fatigue cracks are initiated by the unmelted defects of the sample surfaces. The SLM building process is the most important for the improvement of fatigue strength. Moreover, the crack propagation mechanism is revealed by fracture analysis.

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