Heat Treatment Effect on the Mechanical Properties of AlSi10Mg Produced by Selective Laser Melting

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ABSTRACT

Selective laser melting (SLM) is one of the laser powder bed fusion (LPBF) methods, and parts are built up layer by layer during the melting process. The SLM additive manufacturing was used to produce light-weight parts for the automotive and aerospace industries. The main aim of the research is to improve the mechanical properties and compare them with those of conventionally cast Al6061alloy. In this work investigated mechanical properties like tensile strength, yield strength, and elongation of SLM produced by AlSi10Mg alloy. The conducted tests (conversional and SLM parts) were built in build condition (room temperature) and preheated to 200°C/2 hrs. It is shown that AlSi10Mg parts were given better results compared with conventionally cast Al6061. The SLM-AlSi10mg alloy mechanical properties (as built at room temperature and preheated to 200°C/2 hrs condition) of tensile strength increased from 333 to 342 MPa, yield strength from 79 to 121 MPa, elongation of 5.56 to 10.33%, and hardness 125±5 to 129±5 HV with a high density of 2.66 (99.6%).

KEYWORDS

Laser Powder Bed Fusion; Selective Laser Melting; AlSi10Mg Alloy; Mechanical Properties; Microstructure Evaluation; Hardness and Density.

INTRODUCTION

Rapid manufacture (RM), rapid prototyping (RP), additive manufacturing (AM), and additive layer manufacturing are all terms used to describe the process of building components layer by layer. SLM is a layer-up-layer AM fabrication technique that can be used to create complex, customer-specific structures from metal powders [1,2]. The laser additive manufacturing (LAM) process consists of four processes: wire feed, powder feed, powder bed, and other processes [3,4]. The four technologies are layered in an additive approach. The 3D CAD (computer aided design) geometry is layer by layer (such as sliced) into the thin layers and with slice files, each additive layer manufacturing (ALM) method creates physical AM parts in the SLM process based on the given process parameter [5,6]. In comparison to other ALM process pathways, manufacturing components using powder bed fusion (PBF) provides the most geometrical flexibility and accuracy, producing a full dense sample of 99.95 % [7,8]. Many factors affect the final AM part quality of an SLM printed sample based on material properties (such as morphology, powder size, and distribution) [9]. Another significant component is the laser heat input, which limits the degree of powder particle consolidation defect shape formation by causing turbulence in the melt pool, which can generate a keyhole defect [10]. This is particularly relevant in the space industry and automobile industry, where aluminium alloys are commonly used [11].

The specific applications for AlSi10Mg alloys used in different industries (aerospace, biomedical, and automobile manufacturing industries) are due to their light weight, recycling, high mechanical properties, and low thermal expansion [12]. The AlSi10Mg alloy parts are manufactured by LPBF-SLM (ASTM/ISO 52900). The mechanical
tensile properties of samples are prepared in horizontal build orientation (X-direction) because it is much stronger than vertical samples (Y direction) from the literature review [13]. The tensile test yields high properties (as built and preheated at 200°C) when compared to Al6061 casting material [14, 15]. The material's ductility was improved by a stress-relieving heat treatment at 200°C for 2 hours, which resulted in the alteration of Si-rich cellular borders [16,17]. It is known that structural evolution during heat treatment has an impact on mechanical properties measured at high temperatures, particularly tests like fatigue and mechanical properties, which are improved [18]. The strength of an AM part is primarily determined by process parameter variation and post-processing [19,20]. Previous studies on mechanical properties have used high laser power in watts, scan speed in mm/s, and hatching distance in m [21]. The AM strength depended on the process parameters and build orientation [22].

Previous work of mine investigated optimised process parameters with a fully dense and defect-free component [23]. The mechanical properties of tensile tests with different conditions of AlSi10Mg alloy were conducted using the optimal process parameter [24].

**EXPERIMENTAL DETAILS**

The metal powder of AlSi10Mg alloy chemical composition, which has been mentioned as shown in table 1, is supplied by SLM solution group AG, Germany. The powder particle size distribution ranges from 20–63 μm. The powder particle size distribution range in the SLM printing process is observed by the scanning electron microscope (SEM). The powder weighted residual is 0.694%, specific surface area is 0.154 m²/g, surface weighted mean is 38.8 μm and volume weighted mean is 43.505 μm. The conducted power particle size distribution by sleeve analysis at ARCI, Hyderabad, India is shown in figure 1.

**Table 1. Chemical composition of AlSi10Mg alloy**

<table>
<thead>
<tr>
<th></th>
<th>Al</th>
<th>Su</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>0.05</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>0.05</td>
<td>0.15</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 1.** a) SEM powder particles analysis; b) Powder particle size distribution

The SLM-AlSi10Mg and Casting Al6061 specimens are prepared for tensile testing as per ASTM standard E8/E8M. The circular-bar rod specimen dimensions are; total diameter of 10 mm with a length of 100 mm; gauge diameter of 6 mm with a length of 25 mm and a fillet radius of 6 mm as shown in figure 2.
The tensile test specimens were built by an SLM (M280 2.0) solution equipped with a 280×280×365 mm building chamber and laser power up to 400W (Yb: YAG fibre laser) as shown in figure 3. Used optimal process SLM parameters, i.e., laser power, hatching strategy, scan speed, etc. The following process parameters are considered for this experimental research work: the build temperature is kept at 150°C, the laser spot diameter of 75 µm, layer thickness of 30 µm, laser power of 225 W, the scan speed of 500 mm/s, and the hatching distance of 100 µm. To avoid the pick-up of interstitial oxygen, the SLM manufacturing was carried out in an inert argon environment (lower than 0.2%).

RESULTS AND DISCUSSION

In this work conducted tensile testing at different temperature conditions of AlSi10Mg samples fabricated by SLM. The design of experiment procedure can be summarised as follows:

- Made from AlSi10Mg sample with optimal process parameters
- Accordingly, they used optimal process parameters by layer by layer simulation.
- Developing the experimental design for two different temperature conditions.
- An experiment was conducted as per the DoE.
- The output response selection is a tensile test.
- Developed Finite Element Analysis (FEA-mathematical model) using experimental results.
- Record the output response and compare it with the casting material of Al6061.
AM Simulation

The AM simulation was most important before preparing the SLM printing process started (i.e., saving time, cost, and material). According to the AM simulation results, we have observed the AM part displacement and temperature operating in the SLM process as shown in figure 4. AM part performance is dependent on AM simulation because as laser power increases, so does laser density (i.e., AM parts have experienced deviation and distortion due to high temperature, which is also known as geometric dimensioning and tolerance).

![Image of AM simulation results](image)

**Figure 4.** a) Thermal simulations of displacement and b) SLM printing temperatures used in printing process.

Mechanical Testing

The circular rod-shaped ASTM samples were manufactured by SLM using optimal process parameters that produced the lowest porosity with a high-density component, and all the samples were printed in the horizontal direction. The AlSi10Mg parts were printed as horizontal building orientation and the mechanical tensile test samples were performed according to BS EN 2002-1:2005 (aerospace series) and also followed tensile test standard E8/E8M. All six AlSi10Mg alloy samples were fabricated as per given process parameters. All samples were tested at two different conditions, i.e., as built conditions and preheated conditions at 200°C/2 hrs. The tensile test geometry is shown in figure 5.

![Image of mechanical testing setup](image)

**Figure 5.** a) Machine and b) Printed AM samples
The mechanical properties graph results obtained from the tensile tests done at two different conditions with braked specimens are shown in figures 6 and 7. All the mechanical tensile test results are considered the average of the tested 3 samples, and the results are summarised in table 2. Mechanical properties of produced SLM-AlSi10Mg, Al6061 casting material, literature survey, and simulation results were compared. The highest ultimate tensile stress (UTS) value was obtained by preheating SLM-AlSi10Mg for 2 hours at 200°C (i.e., 342 MPa), and the lowest value was obtained as built casting material Al6061 (i.e., 220 MPa). Finally, observed highest strength value for AlSi10Mg was due to less defects and porosity.

Table 2. Experimental procedure under different treatment

<table>
<thead>
<tr>
<th>No. of Sample</th>
<th>Conditions</th>
<th>Temperature (°C) / 2hrs</th>
<th>Durations (hrs)</th>
<th>Yield Stress (MPa)</th>
<th>Tensile Stress (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Preheated (AlSi10Mg sample)</td>
<td>200</td>
<td>2</td>
<td>121</td>
<td>342</td>
<td>10.33</td>
</tr>
<tr>
<td>3</td>
<td>As-Built (AlSi10Mg sample)</td>
<td>None</td>
<td>None</td>
<td>79</td>
<td>333</td>
<td>5.56</td>
</tr>
<tr>
<td>3</td>
<td>Preheated (Al6061 sample)</td>
<td>200</td>
<td>2</td>
<td>61</td>
<td>232</td>
<td>4.9</td>
</tr>
<tr>
<td>3</td>
<td>As-Built (Al6061 sample)</td>
<td>None</td>
<td>None</td>
<td>42</td>
<td>220</td>
<td>3.3</td>
</tr>
</tbody>
</table>

Figure 6. (a) Stress strain curve for SLM parts (b) As built conditions braked specimens.
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Figure 7. (a) Stress strain curve for SLM parts (b) braked specimens as preheated conditions at 200°C/2 hrs.

After completing experimental work, consider output values as load and SLM data sheet values as young modulus of 75±10 GPa, nu 0.330 g/mm³, yield stress 250 MPa, and co-efficient of thermal expansion 27×10⁻⁶/k for AM simulation. Figure 8 depicts the simulation results, which show a von Mises stress of 348.7 MPa, a yield stress of 78.1 MPa, and an elongation of 0.27%.

Figure 8. AM part simulation of stress results.

The as-built and preheated specimens show high tensile strength values with little elongation due to the very fine microstructure resulting from the SLM build process. Before parts printing preheated the build chamber, a high amount of residual stress was released. The tensile strength of AlSi10Mg alloy (as built and preheated conditions) results in increased yield stress (YS), ultimate tensile stress (UTS), and elongation (%) as shown in table 3. The AlSi10Mg alloy of Si, which was preheated at 200°C for 2 hours, is dominantly responsible for the strength increase and a considerable increase in residual stresses, with no change in the eutectic microstructure. The heat treatment process reduces residual stresses and increases strength. The as-built conditions for the AlSi10Mg/Al6061 material yield stress (YS) of 79 to 42 MPa, ultimate tensile strength (UTS) of 333 to 220 MPa, and elongation (E) to failure of 5.56 to 3.3%. The preheated 200°C AlSi10Mg/Al6061 material results are as follows: yield stress (YS) of 121 to 61 MPa, ultimate tensile strength...
(UTS) of 342 to 232, and elongation (E) to failure of 10.33 to 4.9%. Finally concluded that the preheat of SLM-AlSi10Mg parts is always greater than that of the casting Al6061 material as shown in figure 9.

**Figure 9.** Comparison of (a) as built & preheated of AlSi10Mg, and (b) Casting Al6061, literature survey, experimental and simulation results of (YS & UTS)

**Table 3.** Comparison of results of casting 606 and literature survey (YS & UTS)

<table>
<thead>
<tr>
<th>Comparison of work</th>
<th>Increment YS in (%)</th>
<th>Increment UTS in (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casting Material</td>
<td>40 %</td>
<td>35 %</td>
</tr>
<tr>
<td>Literature survey</td>
<td>10 %</td>
<td>8 %</td>
</tr>
</tbody>
</table>

**Hardness and density**

The Vickers hardness and density results are based on the optimised process parameters. The hardness and mechanical property values are mainly depend 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 grammes each held for 10 seconds are given in table 4. The hardness was measured in the 200°C range as a function of the stress reduction treatment temperature and it was found that the high hardness of the AlSi10Mg alloy is as shown in the table. The SLM part of Vickers hardness is much higher (40%) than the cast Al6061 material. On the table when preheated to 200°C the hardness increased from 126±5 to 129±5 HV. The higher temperatures cause the alloy's inherent strength values to decrease (reducing the yield of the material), which is in line with typical behaviour in such situations. The prepared samples were subjected to density testing by the Archimedes standard principle, used by xylene water. The theoretical density of AlSi10Mg alloy powder (ρt) is 2.67 g/cm³ and, after SLM, manufactured parts have the highest density of 2.66 (99.6%) g/cm³. The decrease in laser power, density, and hardness also decreased. The increase in s s speed then hardness increased and density decreased due to porosity. The density of AlSi10Mg and Al6061 is almost the same; there is no difference with different conditions.

**Table 4.** Microhardness results of AlSi10Mg and Al6061 alloy under the different conditions.

<table>
<thead>
<tr>
<th>Different conditions</th>
<th>Microhardness in HV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preheated (200 °C) (SLM AlSi10Mg Printed sample)</td>
<td>129±5</td>
</tr>
</tbody>
</table>
Microstructure Evaluation

The characterization of the microstructure evaluation was conducted by SEM at different magnifications and with high resolution. The obtained microstructure used optimal process parameters and achieved a defect free component with a high density of AM parts. The SEM is used for microstructure characterization at different magnification levels, as shown in figures 10 and 11. In terms of strength and performance, the hatching distance was the most important factor. The pores can be divided into spherical pores and irregular pores. The cracks are observed along with the horizontal direction of the structure. Due to the poor wettability of oxides and metals, long cracks were formed and spread along the surface. Due to the low cooling rate, some of the AlSi10Mg powder particles are formed as a result of oxidation during the SLM process. The bonding, porosity, and pores of the as-built and preheated conditions of SLM-AlSi10Mg show no significant difference after experimental microstructure observation.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-Built (SLM AlSi10Mg Printed sample)</td>
<td>126 ±5</td>
</tr>
<tr>
<td>Preheated (200 °C) (Casting Al6061 sample)</td>
<td>109±5</td>
</tr>
<tr>
<td>As-Built (Casting Al6061 sample)</td>
<td>98±5</td>
</tr>
</tbody>
</table>

Figure 10. Microstructure of 225 watts / 500 mm/s with different magnification.

Figure 11. Microstructure mid range at 225 watts / 500 mm/s.
**CONCLUSION**

The SLM of AlSi10Mg parts is manufactured for mechanical properties (ultimate tensile stress, yield stress, elongation, hardness, and density) at two different conditions (i.e., room temperature and preheated at 200°C). Because of the higher mechanical properties of AlSi10Mg, it is comparable to cast Al6061 material. The AlSi10Mg material had a higher density because of the very fine microstructure with low defects and fine powder particle distribution of the Si phase. This research study has shown the following:

- The main effect of optimal process parameters on the porosity (pores and other defects) of AlSi10Mg alloy SLM printing. The laser density was calculated at 150 J/mm³ (laser power of 225 watts, scan speed of 500 mm/s, hatching distance of 100 µm and layer thickness of 30 µm).
- The build direction was the most important role in SLM and was given a horizontal orientation for all samples. The AlSi10Mg material is given higher strength (as built and preheated conditions) than the Al6061 material due to its fine microstructure and less defects.
- The AlSi10Mg has UTS of 333 MPa, YS of 79 MPa, an elongation of 5.56%, and a hardness of 126 ± 5. The UTS of 342 MPa, YS of 121 MPa, elongation of 10.33%, and hardness of 129 ± 5 were obtained after 2 hours of mechanical testing at 200°C. With all conditions, there is little difference in density between AlSi10Mg alloy and Al6061 material values of 2.66 (99.6%) g/cm³.

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