

Fracture and fatigue behaviour of AlSi7Mg0.6 produced by Selective Laser Melting: effects of thermal-treatments

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ABSTRACT

In the aerospace sector, aluminium alloys are largely adopted for primary and secondary structures and Additive Manufacturing (AM) processes are receiving more and more attention to produce metal parts with complex geometry, lighter and with additional functional properties. In this view, the influence of different manufacturing parameters on microstructures and mechanical properties of AlSi7Mg0.6 aluminium alloy realised by Selective Laser Melting (SLM) is investigated in this research adopting different experimental techniques. Results highlight the effects of position on the build platform and thermal-treatments on fracture and fatigue responses of the manufactured samples.

Keywords: additive manufacturing, post-processing, Al-alloy, mechanical properties

1 INTRODUCTION

The application of additively manufactured metal components in the aerospace sector is attractive due to a number of potential benefits. Engineers have the possibility to obtain optimized and lightweight structures thanks to the design freedom granted by additive manufacturing (AM) technology. However, there are a number of challenges to be solved before AM can be fully utilized for critical structural component. One of the major issues concerns the understanding of the link between fabrication process, post-processing and resulting mechanical properties [1,2]. Important requirements for the application of these materials produced by AM are strength, structural durability and corrosion resistance comparable or even superior to materials produced by conventional technologies. In this view, post-processing, such as thermal-treatment, Hot Isostatic Pressing (HIP), surface finishing play crucial role to reach these requirements [3–5]. However, compared to conventional technologies, such as casting, AM processes can give materials with completely different microstructure and the application of standard heat treatments, generally used for aluminium alloy in the aerospace field, may results in unexpected mechanical response. Dedicated post processing parameters have to be applied and further research is needed to understand how heat treatments change the microstructures and mechanical properties of additively manufactured aluminium alloys.

The present research investigates the influence of heat treatments on microstructures and mechanical properties (static and fatigue) of AlSi7Mg0.6 aluminium alloy samples realised by Selective Laser Melting (SLM). Samples are fabricated at different locations on the building

platform in order to evaluate the effect of this processing parameter on their mechanical properties.

During SLM production process, the metal undergoes to extremely rapid super-heating and under-cooling, generating ultrafine microstructure (-Al matrix super saturated with Si and Mg) and high residual stresses inside the as-built material, thus, it is fundamental to perform a stress relieving treatment in order to release the thermal stresses generated during SLM process. Such treatment results in a reduction of static tensile strength, with an increasing of ductility, as compared to the as-built condition. Similar results have been recently reported in other researches [6,7]. Furthermore, considering fatigue response, it emerges that the performance of the SLM manufactured material is slightly lower than the one exhibited by the cast alloy [8]. The obtained results indicate that post-processing procedures established for standard technologies are not suitable to increment mechanical properties of the selected alloy produced by SLM technique but they have some positive effect such as the homogenization of the properties of the produced components.

2 EXPERIMENTAL PROCEDURES

2.1 Material and manufacturing

A Renishaw AM250 SLM was employed for producing the test specimens. The machine is equipped with a 200 W fibre laser working in pulsed mode by power modulation, producing a spot diameter of 75 μm at the focal point. Prior to processing, vacuum is applied (oxygen level lower than 1000 ppm), and the working chamber is filled with Argon. No preheating was applied to the platform. The powder used is alloy AlSi7Mg0.6 (A357) produced via Gas Atomization (LPW Ltd, United Kingdom). The powder Particle Size Distribution follows a lognormal distribution with a mean particle size of 41 μm .

The process parameters selected were optimized in a previous experimentation employing an iso-fluence strategy [9]. The chosen parameters are reported in Table 1. All specimens were built in the vertical direction (specimen axis perpendicular with respect to the build platform plane). The experiments aimed to address the influence of stress relieving on the tensile properties and the position of the build platform on static and fatigue properties.

A total number of 55 samples were produced: 40 samples for fatigue evaluation and 15 samples for tensile characterization. Tensile specimens were divided into two batches: 5 samples were tested as-built, 10 samples were stress-relieved before testing. Stress relieving was applied at 300°C for 2 h. Two different position were investigated: internal and external, as showed in Figure 1. External positions were closer to the gas flow inlet and outlet, which could potentially perturbate the powder bed. Two fatigue curves were generated with 20 specimens for each position on the build platform.

Table 1. Process parameters chosen for the processing of AlSi7Mg0.6 specimens.

Parameter	Value
Power, P	200 W
Exposure time, t	131 μs
Hatch distance, d_h	139 μm
Point distance, d_p	80 μm
Layer thickness, z	25 μm
Energy density, E	94 J/mm^3

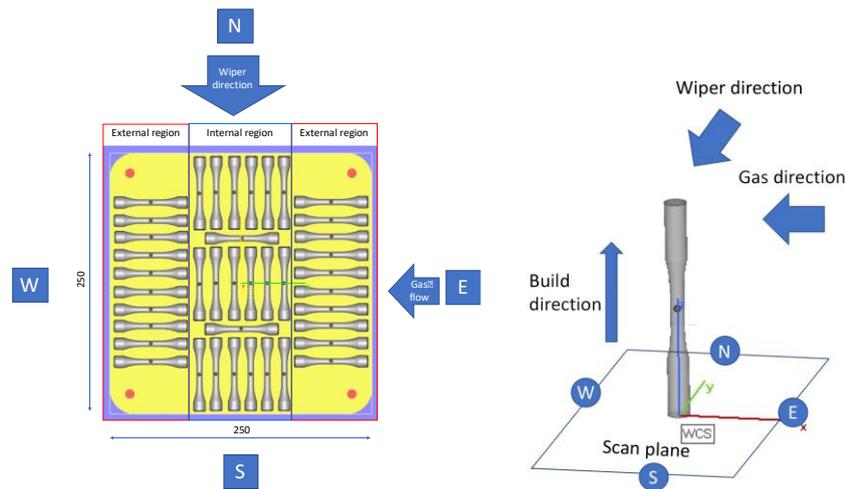


Figure 1. Definition of the internal and external regions on the build platform and reference directions (N,S,E,W).

2.2 Density and surface roughness measurements

Surface roughness was measured using a tactile roughness measurement instrument (Perthometer S6P). The acquisition length was 1.2 mm with a 0.8 mm cut-off length. Average roughness (Ra) was the measured output. This measurement was repeated 4 times for each specimen by rotating the sample of approximately 90 degrees along its axis taking measurements along the four reference directions (N, S, E, W) as defined in Figure 1. Specimens were measured in as-built and sandblasted conditions. Sandblasting was performed manually on all the samples. The duration of the sandblasting was experimentally evaluated to obtain a final average surface roughness lower than 10 μm on all the measured sides. The final procedure involved a sandblasting duration of 200 s per sample.

Density measurement were carried out using Archimede's method. An electronic scale with a kit for density measurement (Sartorius YDK01) was employed. Part density was evaluated as:

$$\rho = \frac{W_a \cdot \rho_w}{W_a - W_w} \quad (1)$$

where W_a is the weight of the sample in water, ρ_w is the density of water and W_w is the weight of the sample in water. Density measurement was replicated three times for each sample, and eventually the mean of the three measures was used.

2.3 Mechanical measurements

Elastic modulus, yield strength, tensile strength, elongation, reduction of area and potential anisotropy of the mechanical properties were obtained from static tensile tests. Experiments were performed according to ASTM E8 standard. A number of five specimens were chosen to be tested for each condition, allowing to identify the variability of the properties. The statistical analysis will give average values for representation of the specimens and will provide information about the uniformity of the material and the repeatability of the test.

Axial force controlled fatigue tests were carried out to obtain the fatigue strength of the materials selected in this study. Fatigue tests were performed according to ASTM E466 standard. The experiments were limited to the testing of axial unnotched specimens subjected to constant amplitude, periodic forcing function in air at room temperature. The geometry of the specimens was the same adopted for tensile tests and indicated in the ASTM E466. The number of the specimens was reduced from the one indicated in the standard in order to

minimize the testing time. The fatigue test will be performed at $R=0.1$ using a 20 Hz sinusoidal wave form under load control to a maximum of 10^7 cycles. The selected testing frequency was in the range indicated by ASTM E466 for which fatigue results are generally unaffected for most metallic engineering materials. $R=0.1$ corresponds to a tension-tension cycle in which the minimum stress is equal to 0.1 times the maximum stress. By keeping the stress ratio R to a lower value, the mean stress remains low and therefore high stress amplitudes can be sustained by the material. The results were plotted on stress vs. cycles-to-failure (S-N) curves. Data analysis was performed according to ASTM E468. Fatigue tests were subdivided in low cycle fatigue range (i.e. 10^4 to 10^6 cycles) and high cycle fatigue range ($>10^6$ cycles). Run-out was fixed to 10^7 cycles. The Staircase method was adopted to evaluate the fatigue limit. For both tensile and fatigue specimens, the fracture surfaces were analysed using scanning electron microscopy (SEM) and the fractography results were correlated with the resulting mechanical properties.

3 RESULTS AND DISCUSSION

3.1 Density and surface roughness of SLM produced specimens

Considering the reference density of AlSi7Mg0.6 (2.68 g/cm^3) all samples produced have a relative density higher than 98.8%. The mean density of samples produced in the “internal” position is $2.656 \pm 0.001 \text{ g/cm}^3$, while for “external” position is $2.653 \pm 0.003 \text{ g/cm}^3$. It can be concluded that the differences are not significant from a practical point of view.

Manual sandblasting was performed for all samples for 200 s; after this process, all R_a values were lower than $10 \mu\text{m}$, as required for fatigue testing. Figure 2 shows the results of the average surface roughness as a function of post-processing and position on the specimen. It can be seen that the sandblasting procedure effectively reduces the average surface roughness to approximately $6 \mu\text{m}$ and provides a more homogenous surface quality across the specimens.

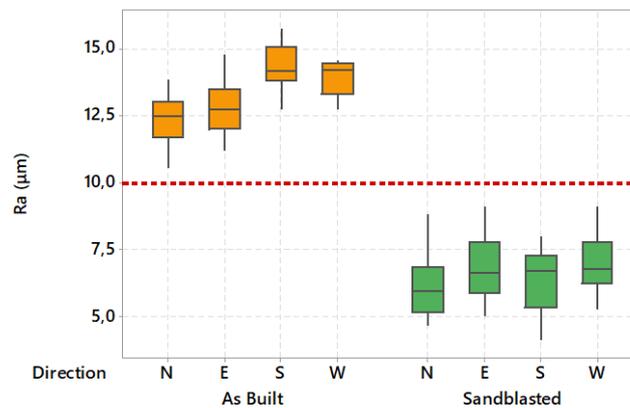


Figure 2. Average roughness of the specimens in as built conditions and after sandblasting as a function of position.

3.2 Tensile static properties

From the data obtained during tensile tests, graphs that illustrate the engineering stress-strain curves have been built. A comparison of stress-strain curves for specimens in different conditions is displayed in Figure 3. It can be observed that stress relieved treatment leads to an increase in ductility and decrease in strength.

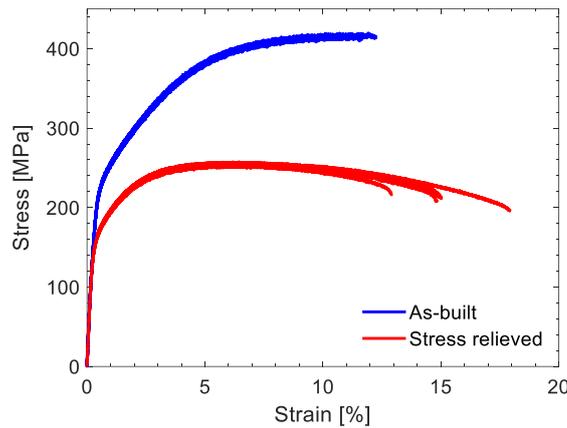


Figure 3: Stress-strain curves for the tested samples: effect of thermal treatment on static tensile properties

Taking the average value with standard deviation of the measured mechanical properties for each condition (as-built and stress relieved) and position on the building plate (internal and external), it is possible to obtain the data shown in Table 2. Looking at this table it is possible to observe that the Young modulus (E) values are comparable for all specimen families, as expected. On the other hand, a significant reduction in strength (yield and ultimate) is detected for stress-relieved samples. An increase in strain at break from as-built to stress relieved condition is also measured. Regarding the position on the building plate, no significant difference in mechanical properties can be reported.

Table 2: Average mechanical properties measured for different samples in tensile mode.

Position	Conditioning	E [GPa]	Yield stress [MPa]	Ultimate stress [MPa]	Strain at break [%]
Internal	As-built	64.1 ± 1.6	222.3 ± 2.0	417.3 ± 1.5	10.8 ± 0.5
Internal	Stress relief	65.0 ± 1.2	167.3 ± 3.4	254.2 ± 1.6	15.1 ± 1.7
External	Stress relief	63.8 ± 1.2	169.1 ± 3.1	254.4 ± 2.4	14.8 ± 0.7

Studying the fracture surfaces, characteristic cup and cone fracture can be observed, indicating the ductile behaviour of the aluminium alloy. In the centre of the most stressed section, some small holes appear (micro-voids), as shown in Figure 4(a). With continuing stress, micro-voids grow and coalesce forming a cavity, which propagates towards the external surface until the final fast fracture. Furthermore, SEM micrographs of the tested as-built samples reveal that the fracture surface is characterized by an extremely fine roughness, consisting of microscopic voids and dimples, which is expected to be formed by the yielding material during the load application. These characteristics indicate the ductile rupture failure mechanism of the material and confirm the fine microstructure formed during the SLM process. The fracture surfaces of the stress-relieved samples appear less brittle and with less cleavage planes than those of the as-built ones. This is coherent with the tensile curves, where the changes in fracture surfaces correspond to the change in ductility. Characteristic cup and cone fracture is more evident and necking is clearly observed for stress-relieved specimens, as depicted in Figure 4(b).

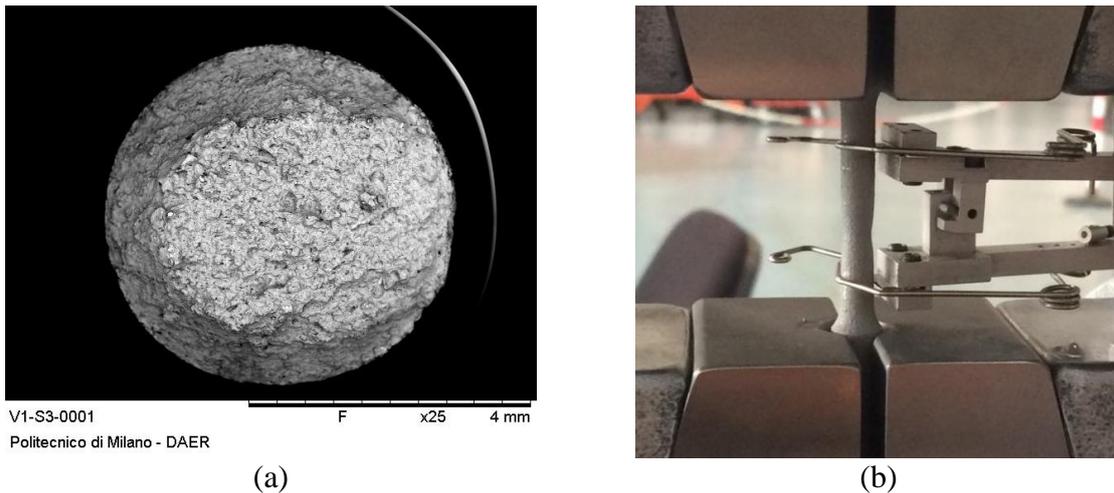


Figure 4: Example of a SEM micrograph of the fracture surface, as-built sample (a) and detail of necking for a stress-relieved sample during tensile testing.

3.3 Tensile fatigue properties

Results of the fatigue tests are presented in Figure 5. The fatigue response for stress-relieved samples located in different position of the building plate does not show significant difference in all regions of the Wöhler diagram. The fatigue endurance calculated with the Staircase method are 127 MPa and 137 MPa for specimens built in the internal and external regions of the build plate, respectively. An initial analysis points out that the position of the sample on the build plate does not strictly affect defect type or quantity and hence the fatigue properties. This limited difference is more likely to be due to the statically nature of the fatigue behaviour. Further analyses, adopting a higher number of fatigue samples, are undergoing for a more clear understanding of this issue.

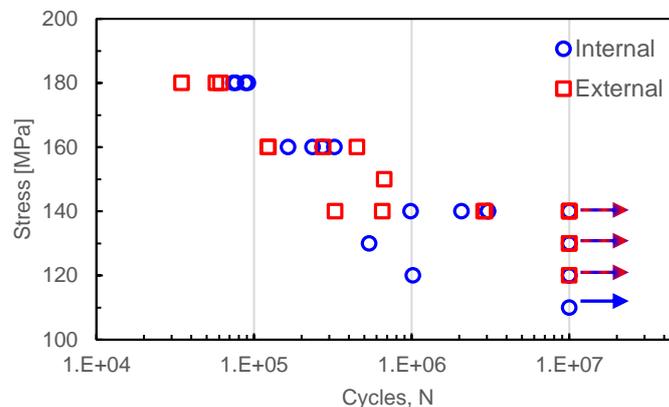


Figure 5: Fatigue response of internal and external samples, arrows indicate run-out samples.

4 CONCLUSIONS

AM techniques are quickly developing in the recent years, as they can provide advantages especially in terms of time between design and production, scrap and weight reduction. Among these techniques, SLM is characterized by the highest industrial maturity, especially concerning Al alloys such as the one tested in this research.

Mechanical testing of the produced SLM samples showed important points concerning the overall production cycle including the stress relieving treatment. The reduction in mechanical response from as-built condition suggests that a dedicated heat treatment must be developed to maintain high mechanical performances. Furthermore, the fatigue resistance is lower compared to the conventionally produced cast alloy, due to the high surface roughness (even after sandblasting post-processing) and the presence of internal defects. These results confirm that SLM is a promising technique, but it still has some disadvantages when compared to more traditional techniques. In particular, improvements in static and fatigue properties are required being critical aspects for primary aerospace structures.

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