

PROCESS OPTIMIZATION AND MICROSTRUCTURAL ANALYSIS FOR SELECTIVE LASER MELTING OF AlSi10Mg

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Abstract

AlSi10Mg is a typical casting alloy which is, due to its high strength/density ratio and thermal properties, highly demanded in aerospace and automotive industries [1]. The alloy combination of aluminium, silicon and magnesium results in a significant increase in strength and hardness which might even reach 300 MPa and 100 HBS, respectively, by applying a proper heat treatment [2]. Selective Laser Melting (SLM) of AlSi10Mg, may be interesting to open new application areas such as heat sinks with complicated geometry [3], and therefore is taken under investigation in this study. The process optimization of SLM for this alloy is not straightforward due to high reflectivity and conductivity of the material. In this study, the main goal is to optimize the process parameters, namely scan speed, scan spacing and laser power, to achieve almost full density and good surface quality taking productivity as a key issue. A relative density up to 99% is achieved with an average roughness (R_a) of about 20 μm measured on horizontal top surfaces while the scanning productivity is about 4.4 mm^3/s . The reasons spherical and irregular porosity formed are investigated. Moreover, microstructural analysis of the SLM samples is conducted.

Introduction

Aluminium as a lightweight material is very attractive for the production of parts that require good mechanical properties in combination with a low weight. The main focus lies on Al-Si alloys, since they are casting alloys that are also suitable for welding. AlSi10Mg, which can be hardened by applying a specific heat treatment, is relatively easy to process by laser applications due to the small difference between liquidus and solidus temperature compared to high strength aluminium-alloys [2]. The AlSi10Mg alloy is frequently used in aerospace, automotive, chemical and food industry. Its composition according to ISO 3522 can be found in Table 1 [4]. Alloying the magnesium to the Al-Si alloy enables precipitation of Mg_2Si which will strengthen the matrix without compromising the other mechanical properties to a significant extent.

Table 1. Chemical composition of AlSi10Mg [4]

Alloying element	Al	Si	Cu	Mn	Mg	Zn	Fe
wt %	rest	9-11	< 0.1	0.05	0.45-0.6	0.05	< 0.55

Selective Laser Melting (SLM) is an Additive Manufacturing process in which parts are built in a layer by layer manner. A laser source selectively scans the powder bed according to the CAD data of the part to be produced. The high intensity laser beam makes it possible to completely melt and fuse the metal powder particles together to obtain almost fully dense parts. Successive layers of metal powder particles are melted and consolidated on top of each other resulting in almost fully dense parts without any need for post-processing other than surface finishing. A schematic view of the SLM-process and main components of an SLM machine are illustrated in Figure 1.

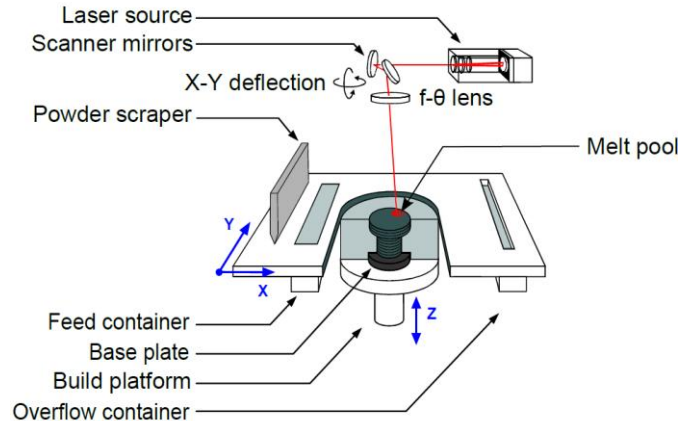


Figure 1: Schematic overview of the SLM- process

SLM of aluminium can offer new opportunities in applications that require internal structures and cavities, like heat sinks and lightweight structures by producing parts with technically sound structures and high freedom in geometrical complexity [1]. In this study, SLM of AlSi10Mg is taken under investigation regarding physical properties like density and surface quality on the one hand, and economical aspects like productivity on the other.

As a preliminary investigation, the SLM of two AlSi10Mg powders from different manufacturers are compared. Their chemical composition, particle size and distribution, flowability and powder production technique may influence the layer deposition and melting behaviour, thus the quality of the final part. As a first step towards the production of three dimensional (3D) AlSi10Mg parts by SLM, single track scans were performed with different scanning parameters to define a process window for this material under these conditions (fiber laser, Argon atmosphere). Thereafter the scanning parameters like laser power (P), scanning speed (v) and scan spacing (ss) are optimized for bulk 3D parts in terms of density, surface quality and/or productivity. Finally, the microstructure and pores that were formed in the SLM-process are taken under investigation.

Experimentation

AlSi10Mg powder was processed on a modified Concept Laser M1 SLM machine [5] that could handle reactive materials with a closely controlled atmosphere. The machine is equipped with a 200 W fiber laser and has a laser beam diameter ($\phi_{99\%}$) of about 150 μm . A wide range of scan speed, scan spacing and laser power was examined. In order to minimize the deformation due to thermal stresses, island scanning (a patented scan pattern from Concept Laser) was used as a scanning strategy, using islands of 5 mm x 5 mm while the islands were shifted 1 mm x 1 mm from layer to layer to avoid any aligned porosity.

The surface roughness of the samples was measured using a contact surface profilometer, Talysurf 120L from Taylor Hobson Ltd. 3D profiles are composed by taking 21 successive 2D roughness measurements of 10mm, with a distance of 100 μm in between these 2D measuring lines.

Density was measured according to the Archimedes method by weighing the samples in air and subsequently in ethanol. Density results are expressed as relative density by taking materials' bulk density as 2.68 g/cm^3 .

Microstructures were observed under a Zeiss Axioscop 40 Pol polarizing microscope.

Experimental Results and Discussion

1. Comparison of two different AlSi10Mg powders

In this study, two different AlSi10Mg powders were used and compared. The powders will further be referred to as S1 and S2.

At first, the chemical composition of both powders was determined by ICP-AES measurement and compared to ISO 3522 standard, see Table 2. The measurements show that the S2 powder has a Silicon wt% of only 8%, which is about 1 wt% lower than the S1 powder, and out of the range for this alloy according to the ISO 3522 standard [4]. According to the literature, the lower Si content may cause a lesser absorption of laser energy, a lower hardness and a larger difference between solidus and liquidus temperatures which will influence the solidification phenomena. [6].

Table 2. Chemical composition of two AlSi10Mg powders, measured by ICP-AES.

Element	Wt% according to ISO 3522	S1 [wt%] based on ICP-AES	S2 [wt%] based on ICP-AES
Si	9-11	9,02	8,05
Fe	<0.55	0,123	0,455
Cu	<0.1	0,006	0,096
Mn	0,05		
Mg	0.45-0,6	0,471	0,542
Zn	<0.10		

The particle size distribution has an important influence on the powder layer deposition and melting behavior. By quantitative stereology on the cross section of embedded powder particles, the average particle size and the particle size distributions were measured. For S1 powder the average particle size $d(v,0.5)$ is 16.3 μm , while for the S2-powder, $d(v, 0.5)$ was determined to be 48.4 μm . The quantitative stereology results also indicate that the distribution of the S1-powder particle size is wider, while the range of particle sizes of the S2-powder is much smaller. The SEM-images confirm these results, as shown in Figure 2. These pictures also show that the S1 powder bears a more spherical morphology and has a smoother surface, while having less satellite-particles. These properties result in a better flowability and a more homogenous powder layer deposition for S1 powder compared to S2 powder which was also evident to naked eye during processing. [7]

S1 powder

S2 powder

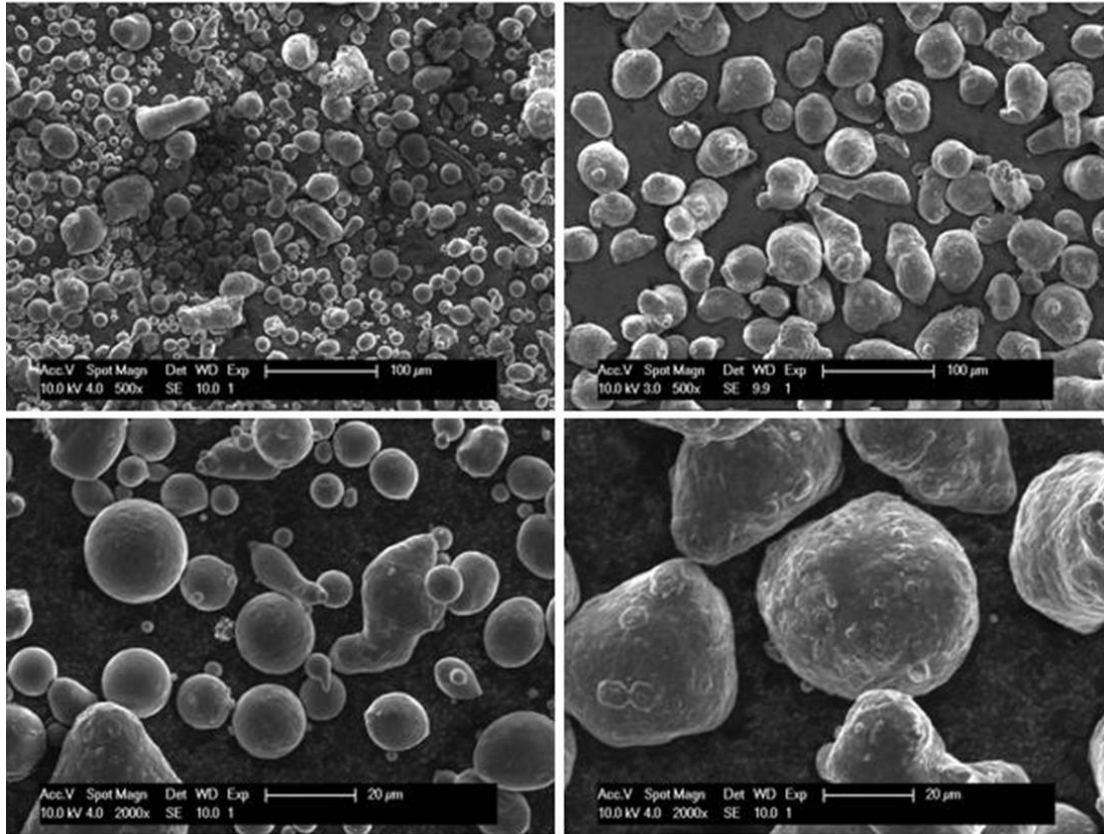


Figure 2: Visual comparison of AlSi10Mg powders by two different suppliers

When producing parts with identical process parameters from these powders (S1 and S2), there is a noticeable difference in density. Relative density results (measured by Archimedes' method, with an absolute density of 2,68 g/cm³) are depicted in Figure 3. The discrepancy of about 1% between density results of S1 and S2 powders may be due to powder morphology and material composition as explained above.

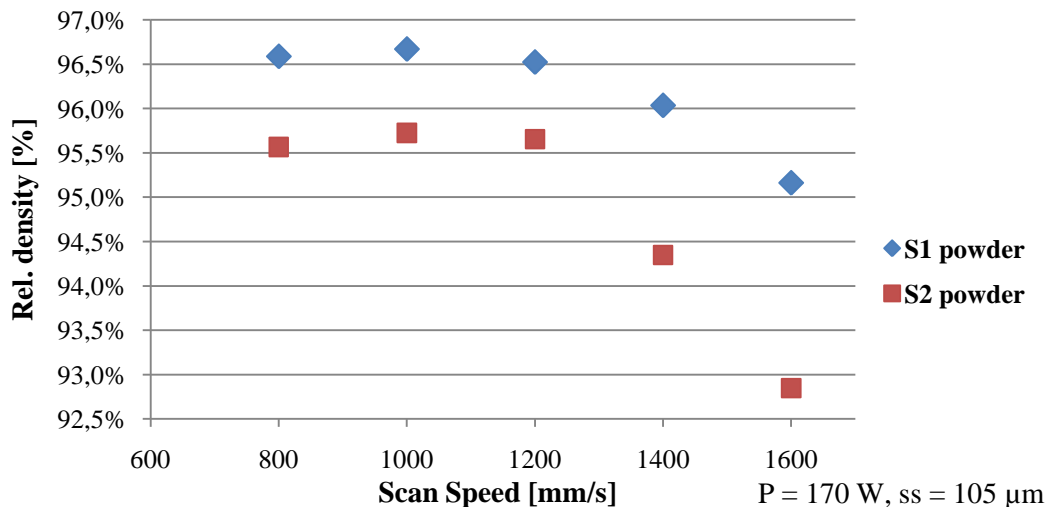


Figure 3: Relative density results for parts produced with identical scanning parameters, but different powders.

The powder comparison indicates more promising results for S1 AlSi10Mg powder for SLM. For this reason, further research described in this paper was conducted with the AlSi10Mg S1 powder.

2. Single Track Scans

In order to determine a process window for Selective Laser Melting of AlSi10Mg powder, single track scans can clearly indicate the nature and shape of the melt pool, depending on the scanning parameters such as laser power and scan speed [8][9]. In this study a laser power between 170 W and 200 W is used, in combination with scan speeds ranging from 200 mm/s to 1400 mm/s.

Our requirements for a scan track to be included in the process window are:

- The scan track must be continuous.
- The scan track must lightly penetrate the previous layer, to accomplish a good connection of the layers. (Wetting of the layer underneath)
- The scan track must be sufficiently high to build up the part
- The connection angle with the previous layer should be about 90° (as indicated in Figure 4) for both a high dimensional accuracy and a high density.

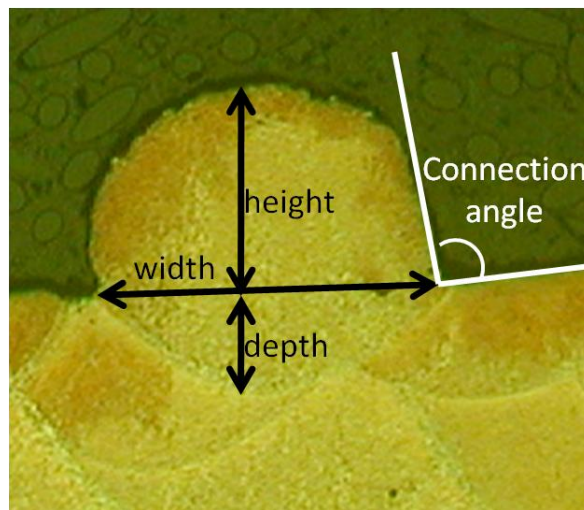


Figure 4: Measuring protocol for comparison of single track scans

To check the scan tracks for the first requirement, a top view image is taken of all the scan tracks with different parameters. These images show that for low scan speeds ($< 600-700$ mm/s), distortion and irregularities appear, probably due to balling phenomenon. When increasing the energy input per unit length (P/v), the melt pool volume increases and the melt pool viscosity decreases, leading to irregularities. When decreasing the energy input per unit length (P/v) by decreasing the laser power, the influence of the recoil pressure becomes more significant and causes the scan track to distort. By increasing the scan speed, the energy input becomes insufficient to fully melt the powder and to partially re-melt the substrate material, leading to the formation of free cylindrical melt pools which are more prone to instability and thus to the formation droplets [10].

A first process window can be defined, based on the first requirement of a continuous scan track: see hatched red area in Figure 5.

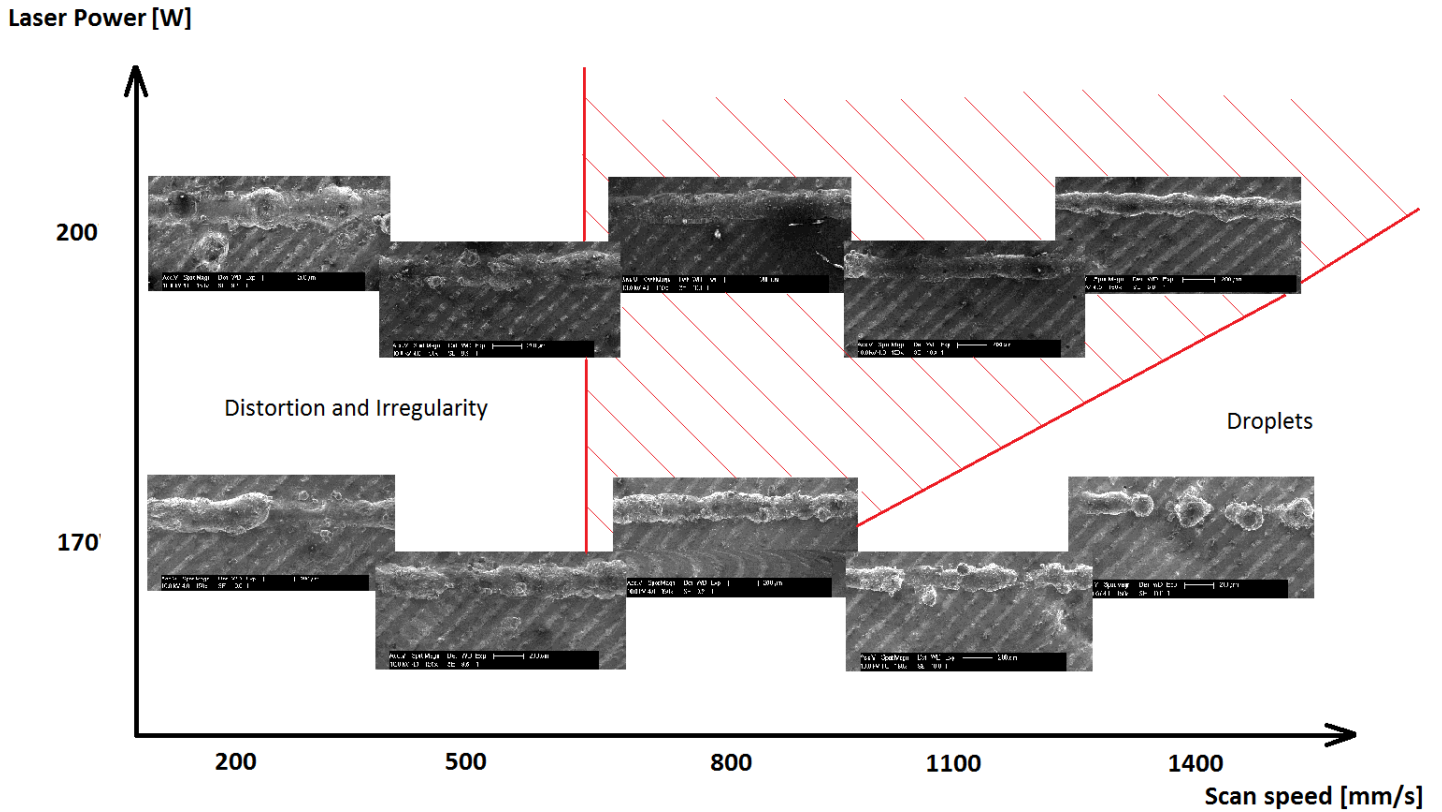


Figure 5: Process window for SLM of AlSi10Mg, based on the top view of single track scans

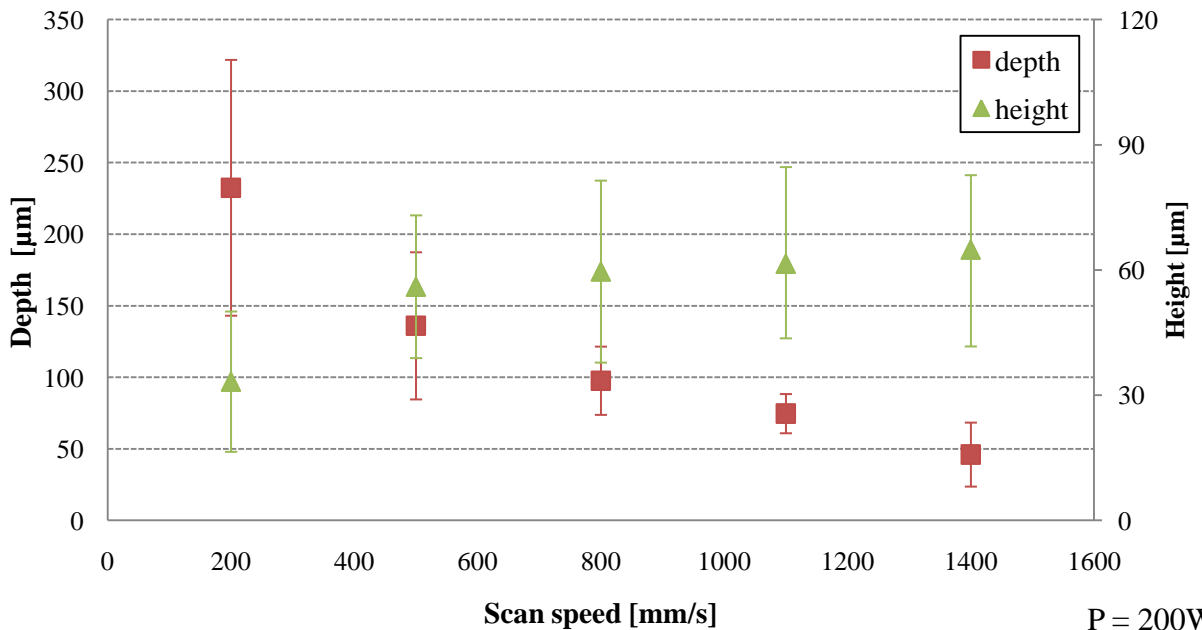


Figure 6: Depth of the re-melted substrate and Height of the melted track in new layer, produced at different scan speeds, error bars showing a confidence interval of 95%

By having a look at the cross-section of the single track scans, other requirements of the scan tracks to be submitted to a process window can be investigated. The width, depth and height of the scan tracks were measured as indicated in Figure 4. For an increasing scan speed, the width and the depth of the scan track decrease and the height of the solidified track increases. These results are depicted in Figure 6. Standard

deviations were determined within a 95% confidence interval. The scan tracks that lie outside the process window are unstable, and thus the results for depth measurements show high standard deviations.

Figure 7 depicts the process window with side cross-sectional views of single scan tracks along the building direction. As observed, a low energy input per unit length ($P = 170\text{W}$, $v = 1400\text{mm/s}$) causes the formation of droplets and very bad wetting, thus a bad connection to the substrate. On the other hand, a very high energy input per unit length ($P = 200\text{W}$, $v = 200\text{mm/s}$) causes a deep penetration and partial evaporation of the powder, resulting in a low height, not fulfilling the third requirement.

Taking all the requirements into account, a final process window can be defined within this range of process parameters as shown in Figure 7.

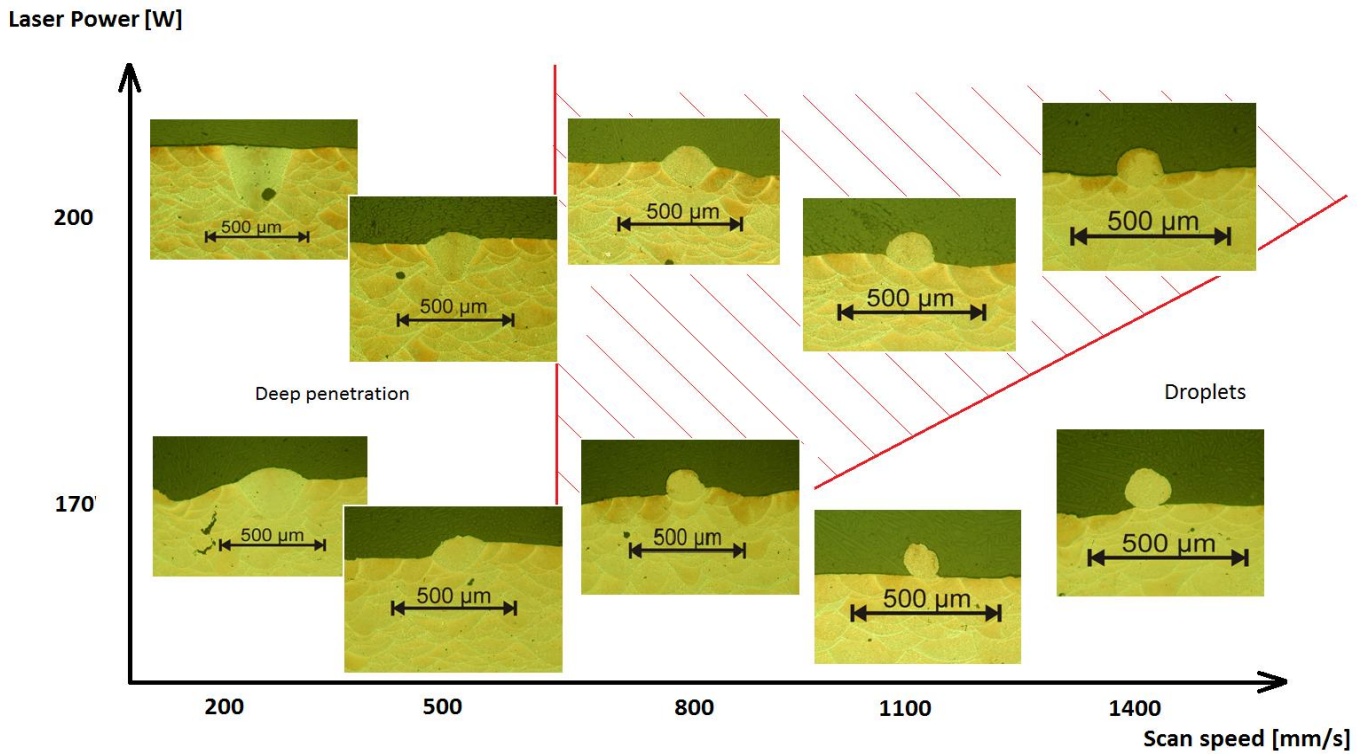


Figure 7: Process window for SLM of AlSi10Mg, within the conditions of this research.

3. Process parameter optimization for density and surface quality

The main objective of this study is to find the optimal parameter-set, in terms of density, surface quality and productivity, for processing 3D AlSi10Mg parts by Selective Laser Melting. The process window resulting from the previous single track scans is used as the basis for this optimization, but measurements were also performed outside the process window for a better understanding of the process. Parts were built with a laser power varying from 170 W to 200 W and a scan speed within the range of 200 mm/s to 1600 mm/s. Initially, the scan spacing, being the distance between two consecutive scan tracks, is kept constant at $105\ \mu\text{m}$ (70% of the spot diameter). The results of density measurements by Archimedes principle are shown in Figure 8a, while Figure 8b only shows the results for high scan speeds to clarify the trend and the maxima that are reached.

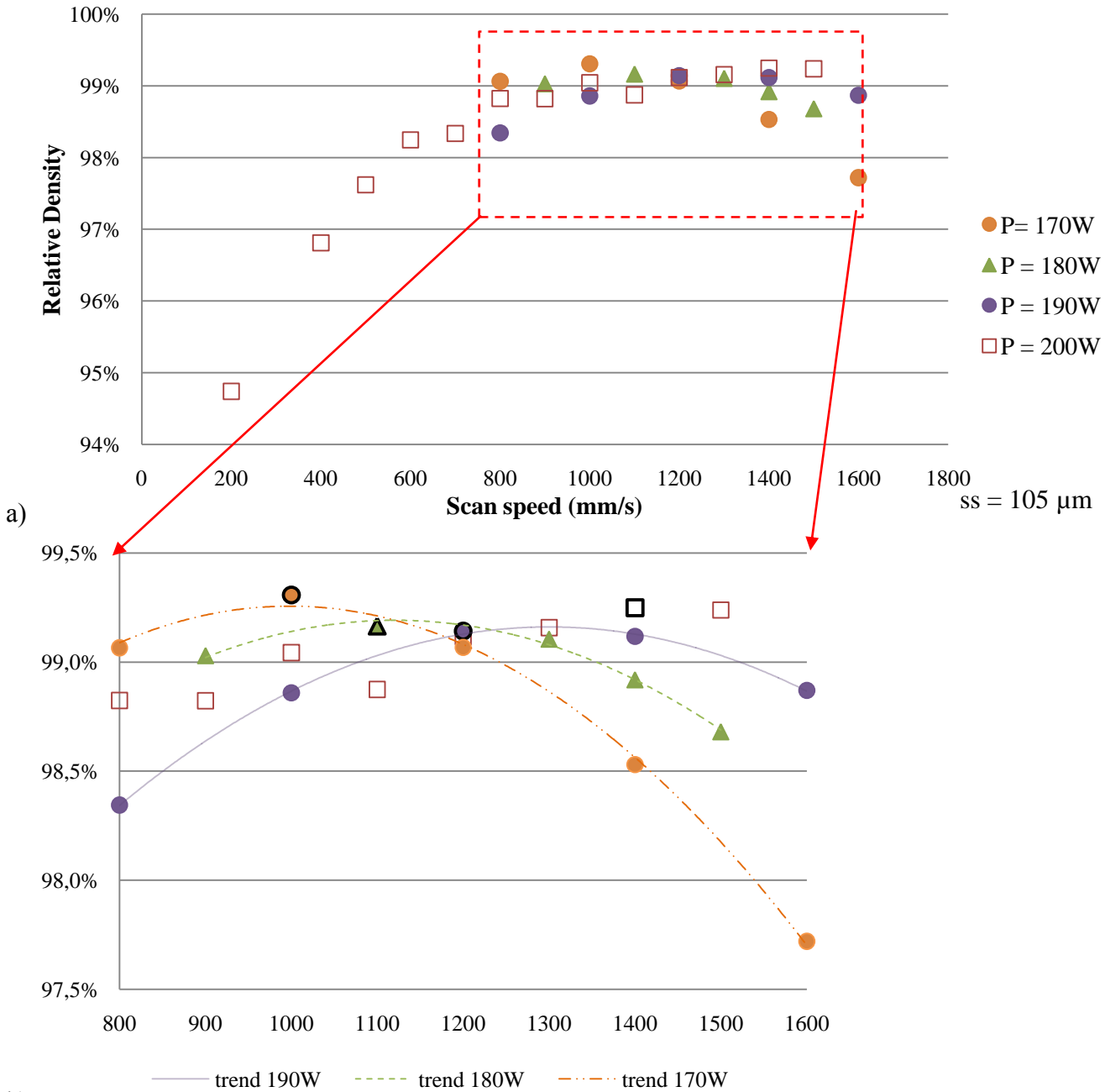


Figure 8: a) Relative density of AlSi10Mg parts produced at different scan speed and laser power.
 b) Clarifying the results at higher scan speeds to indicate trend and maxima

The density of a part increases when increasing the scan speed because the scan track becomes more stable, as seen in the single track scans. Density reaches a maximum at the point of optimal energy input. As expected, for high powers, the optimal energy input, and thus the highest density, is reached at a higher scan speed. For a given laser power, the relative density reaches a maximum at a certain scan speed. These points of maximum density are indicated with a black border in Figure 8b.

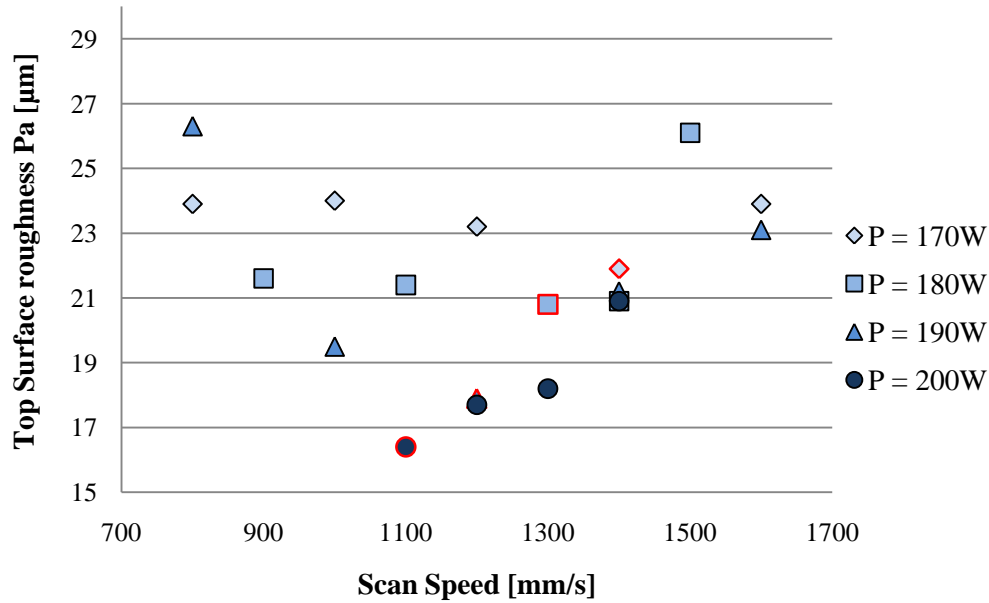


Figure 9: Average top surface roughness of AlSi10Mg parts produced at different scan speed and laser power.

Surface quality can often be an important requirement for SLM-built parts. Average roughness value P_a of the top surface is measured for all the parts and depicted in Figure 9. For a given laser power, the surface roughness value P_a reaches a minimum at a certain scan speed. The higher the laser power, the lower the optimal scan speed. For an increasing energy density, the surface quality will improve as long as the melt pool is stable.

Combining the density and the surface roughness results, two parameter-sets can be defined, depending on the requirements of the SLM-part. The optimal parameter-set in terms of density and productivity is a laser power of 200 W and a scan speed of 1400 mm/s. Combined with a scan spacing of 105 μm , a scanning productivity of 4.4 mm^3/s is obtained, calculated by the product of layer thickness, scan speed and scan spacing [9][11]:

$$\dot{V} = t \cdot v \cdot ss$$

The optimal parameter-set in terms of density and surface quality is a laser power of 200W and a scan speed of 1200mm/s leading to a productivity of 3.8 mm^3/s . Both the optimal density and optimal surface quality parameter sets lie within the process window previously determined for the single track scans.

Density could be improved by optimizing the scan spacing between the scan tracks. The further optimization is conducted for the optimal productivity parameters of 200 W and 1400 mm/s. Based on the measured average track width of 137 μm in the single track scans, the scan spacing is varied between 75 μm and 137 μm so that the scan tracks are not located far from each other. Results of density measurements of parts with different scan spacing parameters are depicted in Figure 10. There is no significant difference in the results. We cannot significantly conclude that scan spacing has an influence on density within this range of parameters.

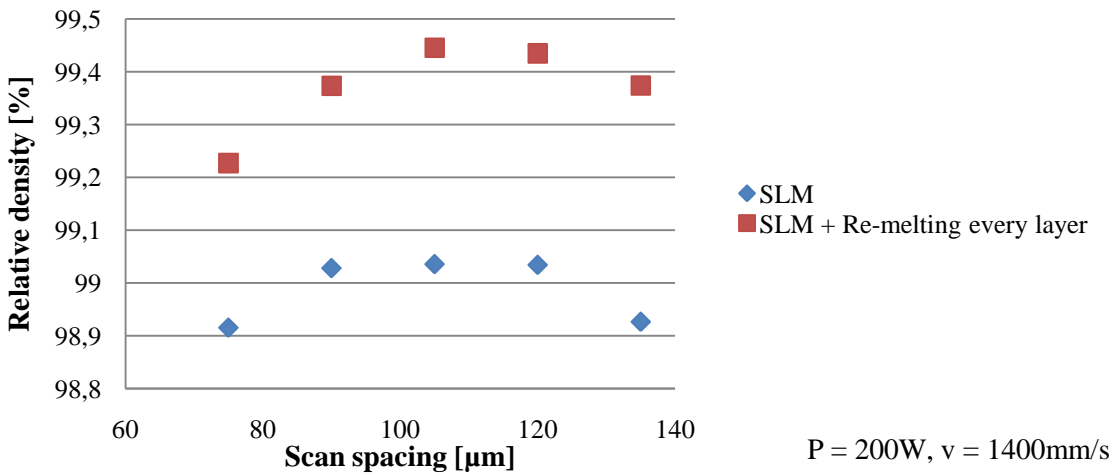


Figure 10: Relative density of AlSi10Mg parts produced with different scan spacing.

4. Microstructural investigation

By means of microstructural investigation, the parts with optimal productivity and density scanning parameters ($P = 200\text{W}$, $v = 1400\text{mm/s}$, $ss = 105\mu\text{m}$) were analyzed by optical microscope (OM).

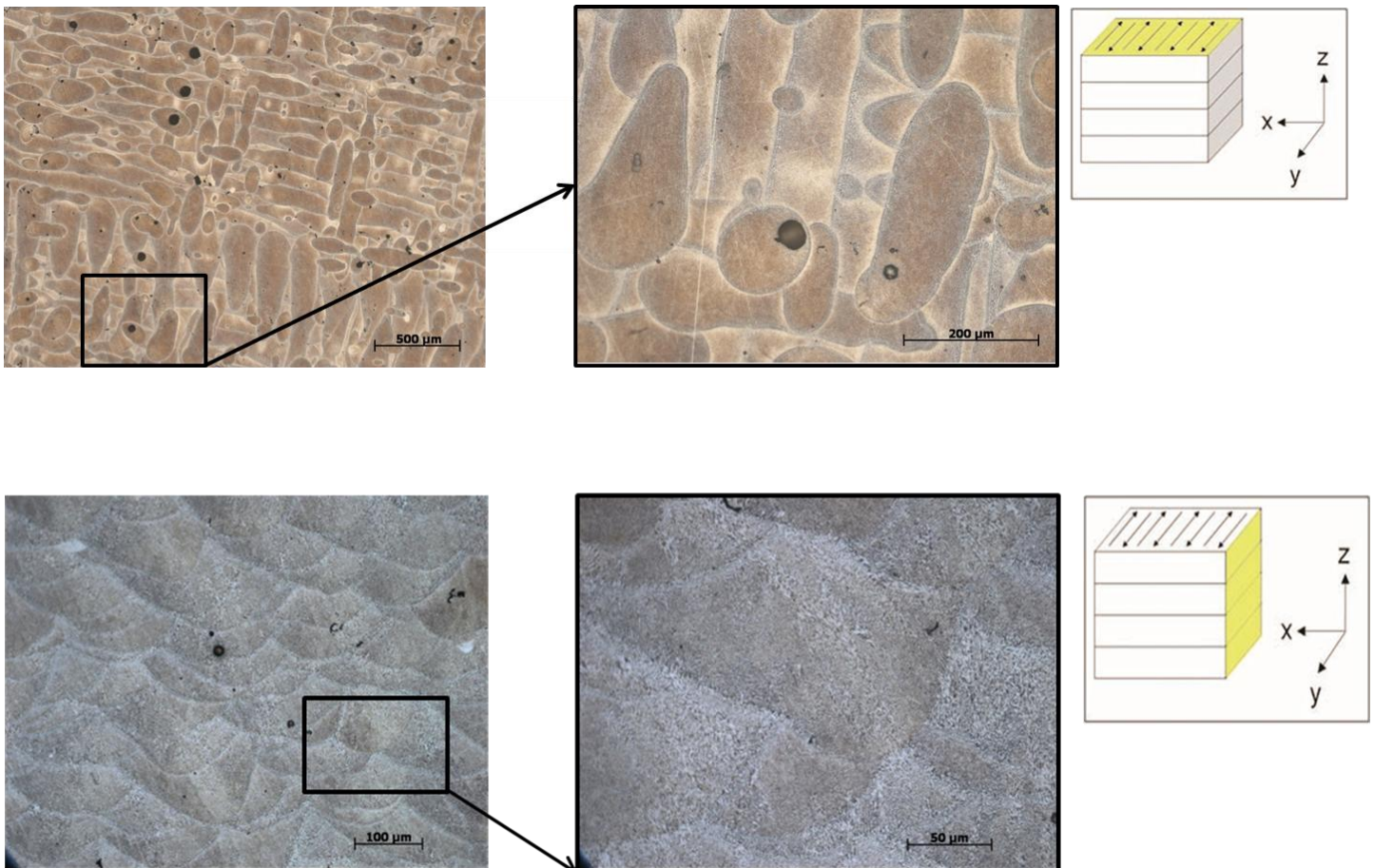
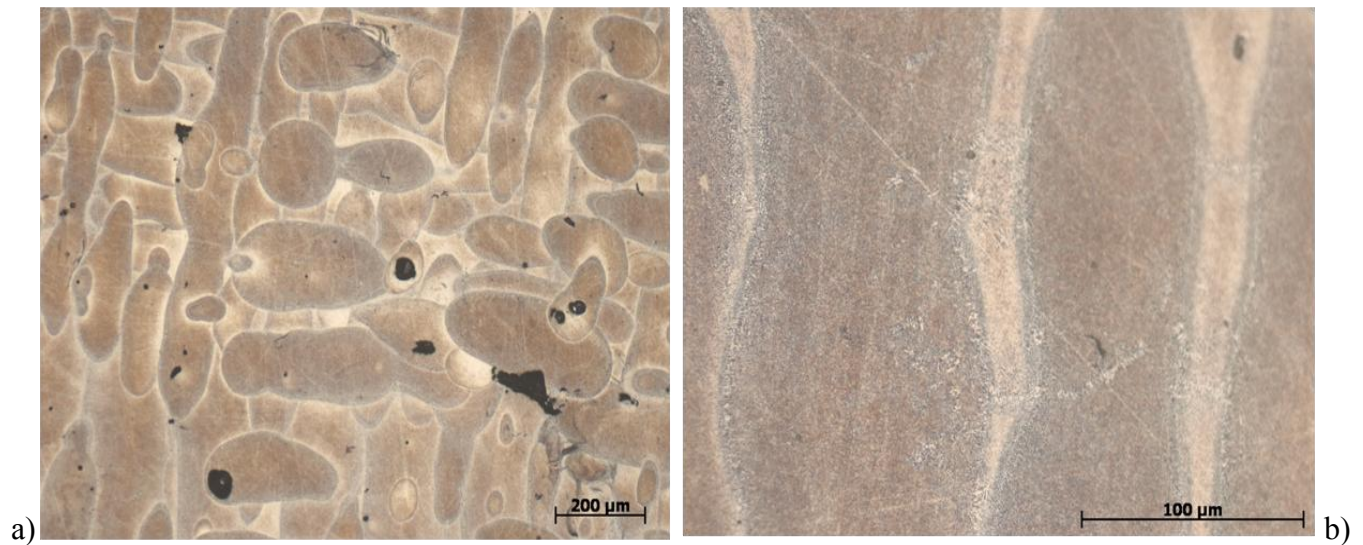


Figure 12: Optical Microscopy images from both top and side view of a part produced with optimal density parameters.

Optical Microscopy images were taken in both the xy-plane (top view) and the yz-plane (side view), as seen in Figure 12. Side view images show that the remaining porosity (0.9%) is indeed low.

Both irregular and spherical pores are observed. Irregular pores are located at melt pool boundaries (Figure 13a). They are formed due to unmelted powder or insufficient overlapping between scan tracks. Spherical pores are generally a consequence of entrapped gasses, which might be oxides or evaporated powder. They are located within the melt pools, as observed in Figure 13a.



**Figure 13 a) Both spherical and irregular pores observed in top view
b) melt pool boundary characterized by a larger grain size.**

By etching the samples, the melt pool boundaries can be detected. Figure 13b is an image at higher magnification that shows that the melt pool boundary is characterized by a larger grain size.

Conclusions

- In SLM of AlSi10Mg, chemical composition, powder shape and size distribution are critical for the powder layer deposition, and thus for the quality of the produced part.
- Single track scans may offer a great amount of information on the behavior of the melt pool. A low energy input per unit length causes the formation of droplets and a bad connection to the substrate. For an energy input that is too high, distortions and irregularities will appear due to big melt pool volumes and recoil pressure aspects.
- A process window was defined where the single track scans fulfill all the requirements of a good and stable scan track for the tested Al alloy.
- Optimal density and surface quality results for 3D parts were obtained and also lie within the defined process window. A higher scan speed (1400 mm/s) was used for high density/productivity demands. A scanning productivity of 4.4 mm³/s was reached to obtain 99.4 % dense parts. The lower scan speeds (1100 – 1200 mm/s) were used for parts with a high demand in top surface quality. Average roughness values of 20 μm P_a value were measured.
- Microstructural analysis showed that both spherical and irregular pores were present in the parts. The SLM-process typifies the very fine microstructure that can be observed under optical microscope. The melt pool boundaries were characterized by a coarser microstructure indicating the heat affected zone.

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