Investigation of Laser Sintered AlSi10Mg Specimens for Density and Surface Roughness

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Abstract AlSi10Mg is one of the most promising alloys in SLM technology due to its low weight and competitive mechanical properties. It gives a good alternative to the conventional manufacturing systems in terms of design flexibility, cost and production time. But the parts made from laser sintering of powder are bound to have rough surface texture. The present study is focused on investigating the impact of process parameters namely laser power, scan speed, hatch spacing and orientation on density and surface roughness of the specimens sintered on selective laser melting of AlSi10Mg. To characterize the parameters, design of experiments was created using RSM and ANOVA analysis was employed to find the factors affecting the responses. The optimization was carried out in MATLAB using optimization toolbox. As per the study, hatch spacing proved to be the major contributor for influencing both density as well as surface roughness.

Keywords: AlSi10Mg, Surface Roughness, Density, RSM, SLM, ANOVA, multiobjective Genetic Algorithm.

1. Introduction

With a very gentle start, rapid prototyping has evolved into additive manufacturing which has given the manufacturing industry a new dimension. It is an umbrella term for a number of manufacturing techniques which are based on different concepts of physics but can be characterized in a single unit in which the products are formed layer by layer. These technologies offer some advantages over conventional manufacturing processes as the wastage of materials are minimal and the extra material left behind can be utilized again without further processing. Another advantage is that there is no design restriction as near impossible to impossible designs can be manufactured using additive manufacturing technology.

Selective Laser melting is one such technology in which metal powder is employed as a cartridge for the production of end-use parts. The input to the system is a CAD drawing which is in .stl format. The drawing is then processed using dedicated software and the layer thickness is selected. The various fabrication factors are then assigned and the data is then forwarded to the machine.

The SLM machine consist of a laser beam focused from the top on the metallic powder bed which is spread evenly using a roller in a closed chamber filled with inert gas. The laser beam is selectively made to scan on the powder and its high energy melts the metal powder at the point of intersection as per the drawing. This molten metal gets sintered with the adjoining grains on solidification. Once one layer is completed, fresh powder is spread on the previous layer and the process is repeated until the whole geometry is formed. This is the reason the process is also called desktop manufacturing and freeform manufacturing. In comparison to traditional manufacturing systems, SLM provides many
advantages like shorter lead time, less to no wastage of materials, mass customization of the products, shorter time to market, and almost infinite flexibility to the designers. But it should not be assumed that the process is all without any drawbacks. The final products show poor repeatability, dimensional inaccuracy, poor surface finish just to name a few. These drawbacks are the research interests for many researchers, scientists and innovators over the past few years since the inception of the technology in the market.

2. Literature Study
Manickavasagam Krishnan [1] et al studied hardness and density on the AlSi10Mg samples with varying values of laser power, scan speed and hatch spacing. They concluded that hatch distance is the most vital parameter to influence the part properties like hardness and density. The reduction in hatch distance leads to curling effects and its increased values can tend to increase the porosity. The interaction between hatch distance and scan speed was considered vital in the study. Alberto Boschetto [2] et al studied the staircase effect in SLS using AlSi10Mg. They proposed a model for the prediction of surface roughness as a function of the geometry of the part. Calignano [3] et al studied the effect of laser power, scan speed and hatch spacing on surface roughness of AlSi10Mg specimens formed by SLM process. The samples were tested for surface roughness before and after shot peening. Taguchi L18 array was used in the study and found the scan speed to be most influential for surface roughness further the shot peening process reduced the surface roughness by 83%.

Iturrioz [4] et al studied the effect of heat treatment on the microstructure and mechanical properties and density on AlSi10Mg samples created in SLM. They concluded that the heat treatment can increase the tensile strength and hardness of the Al alloy if only its treated ay temperature higher than 5500C.

Shigang Bai [5] et al compared the density obtained by Archimedes method with image analysis. Three parameters were studied viz. laser power, scan speed and hatch distance for their correlation with relative density. They concluded that hatching distance is a crucial parameter for density.

E.O. Olakanmi [6] et al corroborated the correlation between the process parameters and densification behaviour in direct laser sintering of Al-12Si specimens. They found that the optimum energy density was 67l/mm3 and any energy level less or more than this will create irregularities on the surface as well as densification behaviour of the Al alloy.

H. Pohl [7] et al suggested that in addition to machine parameters, powder characteristics like size, shape, chemical composition and flowability also contributes in influencing the sintered components. E Atzeni [8] suggested in his study that abrasive fluidized bed to increase the surface finish of AlSi10Mg parts as the post processing. They also studied the various parameters of AFB and optimized for best results.

Biagia Plumbo [9] used the ANOVA statistical approach to analyse the effect of laser power, scan speed and hatch spacing on density, tensile strength and yield strength and concluded that smaller layer thickness and hatch spacing results in better mechanical properties and lead to slow production which can be compensated by higher scan speed.

Lianfeng [10] et al investigated the structural properties of AlSi10Mg for use in aerospace industry. they used the vibration testing technique on direct laser sintered parts and conventionally fabricated parts and found that the structural properties in both the cases was almost same. Bacchewar [11] et al used statistical method ANOVA to analyse the process parameters of SLS for the surface roughness. Wang Rong-Ji [12] et al optimised the seven process parameters for shrinkage ratio using neural network and genetic algorithm.

From the literature review it is found that surface roughness and density is a vital concern in SLS/SLM. The surface roughness is influenced by particle morphology as well as the process parameters like laser power, scan speed, hatch distance, packaging direction, powder shape, size and flow-ability, etc. and many researchers in the past proposed in way or another to tackle this primary problem. While analysing the literature, it is concluded that most of the research is focused on laser
parameter, hatch spacing, powder morphology and energy density. Thus from the literature review laser power, hatch spacing, scan speed and orientation of scanning were selected as the factors to studied and analysed. More over in may literatures there is conflict between the influence of laser power and hatch spacing as major contributor as far as density and surface roughness is concerned.

3. Materials and Methods

Materials

The specimens for the experiment were fabricated using hypoeutectic AlSi10Mg alloy powder provided by EOS GmbH, Germany. It has good melt flowability, corrosion resistance and mechanical properties in addition to its light weight. The powder was spherical in shape with dimeter of 20 to 60 microns. The chemical composition of the material was as follows

| Element | Cu (wt%) | Mg | Fe | Si | Mn | Zn | Other | Al |
|---------|----------|----|----|----|----|----|-------|----|
| Composition | 0.06 | 0.623 | 0.08 | 9.628 | 0.01 | 0.03 | <0.2 | Balance |

Design of Experiments

Laser sintering process includes a large number of input factors. The factors are divided into four categories viz. laser parameters, geometric parameters, material parameters and machine parameters [13]. Since the topic of discussion is density and surface roughness, from the previous literature the factors effecting SR and density have been selected. Thus in the study, Laser power (P) in watts, scan speed (V) in mm/s, hatch distance (H) in mm and orientation (O) in degrees have been analysed. The basis for the selection of range of the parameters was governed by equation 1 [14]

\[ E = \frac{P}{V \times H \times T} \]  

Equation 1

Where, E in J/mm³ is energy density, P is laser power, V is scanning speed, H is hatch spacing and T is layer thickness. The final selection of the parameters was done on the basis of pilot experiments and feasibility study of the machine. The different process parameters and their respective ranges are
shown in table 2. The values of the factors which were kept constant are shown in table 3. The design of experiments was created using box behnken design of response surface methodology. Four factors were selected as discussed earlier and corresponding to these 27 set of experiments were generated with three levels. The factors and the levels are depicted in table 2. The experiments were carried out on EOS P290 workstation at amace solutions, Bangalore in single shot. The surface measurements were taken on Zeta 20 3D optical profilometer. The surface roughness of top surface was considered for the evaluation. The density was evaluated for each sample using Archimedes principle. Analysis of variance (ANOVA) was employed for the evaluation of significant factors and main effects trends. The optimum values were then obtained on optimization toolbox of MATLAB 10 using Multiobjective Genetic Algorithm Solver

### Table 2 Levels of factors for fabrication

| Variable Factors          | Levels |
|---------------------------|--------|
|                          | -1     | 0    | 1    |
| Laser Power (P) in watts  | 300    | 350  | 400  |
| Scan Speed (V) mm/s       | 1500   | 1600 | 1700 |
| Hatch Distance (H) mm     | 0.1    | 0.175| 2.5  |
| Orientation (O) degree    | 0      | 45   | 90   |

### Table 3 Fixed Machine Factors

| Fixed Factors            | Values               |
|--------------------------|----------------------|
| Layer thickness          | 0.06 mm              |
| Laser spot size          | 80 microns           |
| Chamber temperature      | 150 degree C         |
| Sinter scan              | Off                  |
| Roller speed             | 1200 mm/s            |
| Hatch length             | 10 mm                |
| Powder size              | 20 – 60 microns      |

3.1 Fabrication Procedure

The geometry of the specimen was created on CATIA V5 R16 design software. A simple cuboid of size 9mm x 9mm x 6 mm was modelled. The file was converted in .stl format and then opened in magics software to give the layer thickness and the file was ready to be processed in EOS P290 workstation for the final part to be sintered. Each sample was allotted its specified input variable factor at the machine interface. Once the parts were ready in the chamber, the samples were allowed to cool for approximately 4 to 5 hours so that no stresses are induced in the samples or no cracks are formed due to sudden cooling. During the sintering process unidirectional scan pattern was adopted. The geometry of the part samples is as shown in the figure 2
3.2 Measurement of Density
The density was measured using ASTM Standard B311-13 [15], the Archimedes principle. As per Archimedes principle, density can be calculated as follows
\[ \rho = \frac{(m_{\text{in air}} \times \rho_{\text{of liquid}})}{(m_{\text{in air}} - m_{\text{in liquid}})} \] …equation 2
Where \( \rho \) is the density of the sample, \( m_{\text{in air}} \) is the mass of sample in air, \( \rho_{\text{of liquid}} \) is the density of the liquid, \( m_{\text{in liquid}} \) is the mass of sample in water.[16] For the experiment distilled water was used.

3.3 Measurement of Surface Roughness
The surface roughness was measured on Zeta 20 3D optical profilometer. In contrast to conventional microscopes which measures the details at a fixed focal length, a 3D microscope measures the details in a range of height from the measuring plane and at each measuring position it records the exact xy location and height. All this information is then merged to create a complete 3D image. This image has all the crests and troughs and gives a true impression of the surface being measured. In addition to this the zeta 3D software also provides the numeric values of the surface information like average roughness of a particular range, root mean square value of the surface roughness, etc. the samples were tested on zeta 3D optical profilometer for average roughness of the top surface of the specimens. Figure 3 (a) and 3(b) shows the results for one of the samples as produced by the profilometer.

4. Statistical Modelling
In present study, four control variables were selected and the range of the parameters was strictly controlled by equation 1. Laser power, scan speed, hatch spacing and orientation were selected to be varied and the design of experiment was created using box-behnken model of surface response methodology. The three level design and the measured results are as shown in the table 4.
| Experiment No. | Laser Power (W) X1 | Scan Speed (mm/s) X2 | Hatch Spacing (mm) X3 | Orientation (Degrees) X4 | Avg. Surface roughness (microns) F1 | Density F2 |
|---------------|-------------------|---------------------|----------------------|-------------------------|------------------------------------|-----------|
| 1             | 350               | 1700                | 0.25                 | 45                      | 54.81                              | 2.245     |
| 2             | 350               | 1500                | 0.1                  | 45                      | 21.15                              | 2.550     |
| 3             | 350               | 1500                | 0.25                 | 45                      | 53.21                              | 2.666     |
| 4             | 400               | 1700                | 0.175                | 45                      | 37.9                               | 2.420     |
| 5             | 300               | 1600                | 0.1                  | 45                      | 32.54                              | 2.502     |
| 6             | 400               | 1600                | 0.175                | 0                       | 35.61                              | 2.464     |
| 7             | 400               | 1500                | 0.175                | 45                      | 33.48                              | 2.455     |
| 8             | 350               | 1700                | 0.175                | 0                       | 45.6                               | 2.322     |
| 9             | 300               | 1600                | 0.25                 | 45                      | 70.36                              | 2.174     |
| 10            | 300               | 1600                | 0.175                | 0                       | 47.96                              | 2.281     |
| 11            | 350               | 1600                | 0.25                 | 0                       | 53.3                               | 2.224     |
| 12            | 350               | 1600                | 0.175                | 45                      | 41.07                              | 2.491     |
| 13            | 300               | 1700                | 0.175                | 45                      | 49.91                              | 2.316     |
| 14            | 350               | 1600                | 0.175                | 45                      | 42.85                              | 2.370     |
| 15            | 350               | 1600                | 0.1                  | 0                       | 21.51                              | 2.550     |
| 16            | 400               | 1600                | 0.175                | 90                      | 34.82                              | 2.449     |
| 17            | 300               | 1600                | 0.175                | 90                      | 49.24                              | 2.350     |
| 18            | 350               | 1700                | 0.175                | 90                      | 45.45                              | 2.360     |
| 19            | 350               | 1500                | 0.175                | 90                      | 40.86                              | 2.390     |
| 20            | 350               | 1600                | 0.175                | 45                      | 45.42                              | 2.366     |
| 21            | 300               | 1500                | 0.175                | 45                      | 46.9                               | 2.352     |
| 22            | 400               | 1600                | 0.25                 | 45                      | 53.1                               | 2.316     |
| 23            | 350               | 1600                | 0.25                 | 90                      | 54.24                              | 2.257     |
| 24            | 350               | 1600                | 0.1                  | 90                      | 31                                 | 2.517     |
| 25            | 350               | 1700                | 0.1                  | 45                      | 31.8                               | 2.464     |
| 26            | 400               | 1600                | 0.1                  | 45                      | 19.37                              | 2.580     |
| 27            | 350               | 1500                | 0.175                | 0                       | 39.97                              | 2.390     |

Statistical software Minitab 17 was employed for the analysis and modelling of the data presented in Table 3. The regression model thus obtained is presented in the following equations:

\[
F_1 = -238 - 0.334X(1) + 0.300X(2) + 892X(3) + 0.348X(4) + 0.000202X(1)X(1) \\
+ 0.000076X(2)X(2) - 239X(3)X(3) - 0.000469X(4)X(4) + 0.000071X(1)X(2) \\
+ 0.273X(1)X(3) - 0.000230X(1)X(4) + 0.302X(2)X(3) - 0.000058X(2)X(4) - 0.633X(3)X(4) \\
\]

Equation 3

\[
F_2 = -2.53 + 0.00245X(1) + 0.00651X(2) - 6.53X(3) + 0.00021X(4) - 0.000002X(1)X(1) \\
- 0.000002X(2)X(2) - 1.38X(3)X(3) - 0.000009X(4)X(4) + 0.000000X(1)X(2) \\
+ 0.00414X(1)X(3) - 0.000010X(1)X(4) + 0.00217X(2)X(3) + 0.000002X(2)X(4) \\
+ 0.00482X(3)X(4) \\
\]

Equation 4

The response data obtained was also analysed for its consistency for average surface roughness with respect to input variables based on analysis of variance (ANOVA). The initial investigation revealed that there were some insignificant terms in the ANOVA table which were eliminated as their
values were falling outside 95% confidence interval. The more values also increased the complexity of the model.

The model was enriched by eliminating the insignificant terms as per the ANOVA table. After eliminating the insignificant terms, the new values have been shown in table 4.

The response data was further analysed for density as the output parameter using ANOVA again the insignificant values have been eliminated and improved table is presented in the table 5. In both the cases the F-value was falling well in the range of 95 percent confidence level and the model was proved to be adequate.

Table 5: ANOVA for Surface Roughness

| Source               | DF  | Adj. SS  | Adj. MS  | F    | P   | Remarks                  |
|----------------------|-----|----------|----------|------|-----|--------------------------|
| Model                | 14  | 3469     | 247      | 27.83| 0.0 | F critical at 95% is 2.63|
| Linear               | 4   | 3404.53  |          |      |     | F critical < F model, thus the model is adequate |
| Square               | 4   | 19.69    |          |      |     |                          |
| 2 Way Interaction    | 6   | 44.77    |          |      |     |                          |
| Residual Error       | 12  | 106.84   | 8.90     |      |     |                          |
| Lack of Fit          | 10  | 97.27    |          | 2.03 | 0.374 |                          |
| Pure Error           | 2   | 9.57     |          |      |     |                          |
| Total                | 26  | 3575.84  |          |      |     |                          |

Table 6: ANOVA for Density

| Source               | DF  | Adj. SS  | Adj. MS  | F    | P   | Remarks                  |
|----------------------|-----|----------|----------|------|-----|--------------------------|
| Model                | 14  | 415.520  | 29.680   | 20   | 0.0 | F critical at 95% is 2.63|
| Linear               | 4   | 402.695  | 100.674  | 68.95| 0.0 | F critical < F model, thus the model is adequate |
| Square               | 4   | 5.161    | 1.290    |      | 0.503|                          |
| 2 Way Interaction    | 6   | 7.664    | 1.277    |      | 0.541|                          |
| Residual Error       | 12  | 17.521   | 1.460    |      |     |                          |
| Lack of Fit          | 10  | 3.938    | 0.394    |      |     |                          |
| Pure Error           | 2   | 13.583   | 6.792    |      |     |                          |
| Total                | 26  | 433.041  |          |      |     |                          |

5. Results and Discussion

The laser sintered parts are as shown in the figure 4 the SEM images of the fabricated part has also been shown in figure 5 (a), (b), (c), (d).

Figure 4. Laser sintered parts as made.
SEM images of the sintered part at 90 X shows the irregular peaks at the surface of the sintered parts. Further zoomed images at 5000X shows the grains are not melted fully and created voids at and inside the surface which resulted in low surface finish as well as less density in the present case.

5.1 Effect of Process Parameters on Surface Roughness

Figure shows the main effect plot for the input variables vs surface roughness. As per the plot it is observed that the effect of laser power and hatch spacing is much significant as compared to the other two factors. The reasons for these effects have been discussed in detail.

Figure 6: Main effect plot for surface roughness
Figure 6: Main Effect Graph for Surface Roughness

A. Effect of laser power on surface roughness.
From the graph it is clearly understood that the laser power has a great influence on the surface roughness. At lower laser power the roughness level is on higher side. As the levels of laser power increases the surface roughness decreases and the surface gets smoother. As it is evident from the plot that minimum surface roughness was achieved at 400 watts of laser power and at 300 watts laser power the surface roughness was maximum. This may be due to the reason that at higher laser power, the metal powder gets melted completely and gives a better sintering effect. Thus in this way laser power is a major contributor in influencing the surface roughness of the sintered part.

B. Effect of scan speed on surface roughness.
It can be observed from the main effect graph that scan speed is not a very great influencer as far as surface roughness is concerned. The effect is minimal but the orientation of the plot shows that at lower speed of scanning of laser beam the roughness is lower but at higher speeds the surface finish deteriorates as higher speeds that interaction time decreases and thus the melting of metal powder is affected.

C. Effect of hatch spacing on surface roughness.
Hatch spacing is a major contributor in the surface roughness of the parts in laser sintering. At lower values of the hatch spacing, the surface finish is high and it deteriorates as the hatch spacing increases. It is due to the fact that at lower values of hatch spacing the grains are close to each other and better packing of the grains was possible with gives better results for surface finish. At higher values of hatch spacing, the grains are loosely packed and thus the surface roughness level is also high.

D. Effect of orientation on surface roughness
As per the main effect plot, orientation is also not a great influencer in case of surface roughness. It gives almost the same results at all three levels of orientation. Many authors in the past have considered orientation as a major contributor but that is in the case of stair case effect, in case of plane surface the effect of orientation is minor.
5.2 Effect of process parameters on density

A. Effect of Laser Power on density
As the plot depicts, the increase in laser power increases the density of the sintered material. This is because of the reason that more laser power results in more binding energy and more compactness in the sintered part. Less laser power may result in incomplete or less sintering and results in voids and pores on the sintered part. Laser power thus has a great impact on the density of the material sintered on SLM.

B. Effect of Scan Speed on density
As the plot shows, the scan speed’s effect is opposite of what laser power has on density. At lower scan speed the interaction time of laser is more with the grains thus more energy is absorbed by the grains and that result in more melting and thus more compactness in the sintered part. Less interaction time at higher speeds may results in partial melting and thus voids and pores in the sintered parts which ultimately results in low dense part.

C. Effect of Hatch Spacing on density
As per the main effect plot, hatch spacing is the most significant factor for density. At lower value of hatch spacing, the density is much higher as the grains are closely packed. At higher values of hatch spacing the powder is competitively loosely packed and thus density in this case is on lower side.

D. Effect on orientation on density
The main effect plot illustrates that density has almost constant values at different levels of orientations. On varying the value of orientation from 0 degree to 90 degrees the mean density remains around 90%.

5.3 Optimization
The present case has two objectives. First objective is to minimise the surface roughness. Thus it’s a minimisation problem and second objective is to maximise the density, which is a maximisation problem. Thus a multi-objective optimisation was carried out using the optimisation toolbox of MATLAB 13. The multi-objective genetic algorithm was employed with respect to following conditions
Minimize $F_1 = SR(\phi)$
Maximize $F_2 = D(\phi)$
Where $\phi$ is $[X_1, X_2, X_3, X_4]$
Subject to
300≤X1≤400
1500≤X2≤ 1700
0.1≤X3≤0.25
0≤X4≤90
…………….Equation 5

The optimized set of process parameters after applying the conditions on MATLAB optimization tool environment are shown in the figure

Table shows the optimized values of the parameters produced by the multiobjective GA optimization with their predicted response values.

Table 7: Optimized Values of Process Parameters

| SR | Density | Laser Power | Scan Speed | Hatch Spacing | Orientation |
|----|---------|-------------|------------|---------------|-------------|
| F1 | F2      | P           | V          | H             | O           |
| 16.57 | 2.52 | 399.94       | 1554.36 | 0.100         | 0.48         |

Based on the values obtained, confirmation tests were conducted to validate the outcome of the optimization results.

Table shows the predicted and experimental values of the output parameters based on the optimised values of the input factors.

Table 8: Comparison chart for predicted values and experimental values

| Process Parameters | SR Predicted | Experimental | Error | Density Predicted | Experimental | Error |
|--------------------|--------------|--------------|-------|--------------------|--------------|-------|
| Laser Power | 399 | 1554 | 0.1 | 0 | 16.19 | 17.59 | 8% | 2.53 | 2.48 | 5% |

6. Conclusions

In the present study, the effect of process parameters viz. laser power, scan speed, hatch spacing and orientation were studied on surface roughness and density of the laser sintered parts of AlSi10Mg alloy. The investigation was carried out using a design of experiment created by adopting Box Behnken approach of Response Surface Methodology. The statistical models for surface roughness and density are presented using analysis of variance statistical approach. Quadratic response surface
model was developed for the analysis and predicting the significant factors. Thereafter the results and outcomes of the ANOVA analysis are discussed. Following are the interpretations of the study:

1. Hatch spacing is the most significant factor followed by laser power, scan spacing and orientation for surface roughness.
2. Lower values of hatch spacing reduces the surface roughness and with increase in laser power the surface roughness reduces significantly.
3. Scan speed and orientation have less effect on surface roughness.
4. Density is inversely proportional to hatch spacing. Higher values of hatch spacing results in reduced density and visa-versa.
5. Laser power is a direct function of density. Higher the Laser power higher is the density under given circumstances. Much high values of laser power may burn the powder and no sintering will take place.
6. Faster scan speed leads to less exposure and thus density deteriorates. Much slow speeds can lead to more heat accumulation and over-heating.

**Abbreviations**

| Abbreviation | Description                  |
|--------------|------------------------------|
| AFB          | Abrasive Fluidized Bed       |
| ANOVA        | Analysis of Variance         |
| CAD          | Computer Aided Design        |
| RSM          | Response Surface Methodology  |
| SLM          | Selective Laser Melting      |
| SLS          | Selective Laser Sintering    |

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