Research on Improving the Outer Surface Quality of the Parts Made by SLM

BALC Nicolae¹, a *, COSMA Sorin Cosmin¹,b, KESSLER Julia²,c and MAGER Voicu¹,d

¹Technical University of Cluj-Napoca, B-dul Muncii, No. 103-105, Cluj-Napoca, Romania
²Aachen University of applied sciences, Faculty of Mechanical Engineering and Mechatronics, Goethestr. 1, 52064 Aachen, GERMANY

a nicolae.balc@tcm.utcluj.ro, b sorin.cosma@tcm.utcluj.ro, c kessler@fh-aachen.de, d voicumager@yahoo.com

Keywords: selective laser melting, surface quality, scanning speed, exposure time.

Abstract. The paper presents an application of the ANOVA method within the Selective Laser Melting (SLM) process. A new mathematical model was developed, to calculate the surface roughness of the SLM parts made from titanium powder, as function of the important SLM parameters: point distance, exposure time and laser power. Preliminary experiments were undertaken according to the Design Experts work plan and the new mathematical formula was tested by further experimental research, to validate the optimized SLM parameters.

Introduction

The Selective Laser Melting (SLM) process is depending upon many working parameters, which have different influences onto the mechanical characteristics of the parts made by SLM, onto the accuracy, surface quality of those parts and efficiency of this manufacturing process. Since the SLM process was invented in 1995, many studies were undertaken, in order to improve the process parameters and the effects onto the SLM metal parts, [1].

Previous research was undertaken within the Department of Manufacturing Engineering (DME) from Technical University of Cluj-Napoca (TUC-N), in order to study the influence of each SLM parameter, when processing different metal powder, to produce SLM parts, both for industrial and medical applications.

Significant studies on improving the surface roughness of the SLM parts were published in 2006, presenting how the Ra roughness is about 18-20µm, when using Ti6Al4V biocompatible powder [2], [3]. In 2008 an interesting study underlined the importance of optimizing the contour scanning parameters, to improve the surface quality of the SLM parts [4]. Fig. 1 illustrates how an increased scanning speed (from 40 mm/s to 640 mm/s) changes the topology and roughness of the welding line and leads to a higher roughness, if the laser power is constant.

Fig. 1. Surface quality of the SLM parts, [1]

Preliminary experimental research was done, to estimate the mathematical model, which was tested after words, by undertaking different experimental research, [5, 8].

The current SLM technology available at DME allows programming the Outer Boundary set of parameters, within the material file. The Outer Boundary function cumulates three independent process parameters: Expose Time (ET), Point Distance (PD) and laser Power (P). The scanning
speed is programmed by setting values for PD [µm] and ET [µs] and the laser power is configured by the current, the maximum laser power (200 W), corresponds to a 5000 mA current.

The shape and size of the metal powder are influencing the surface quality of the part. Within this research, biocompatible Ti powder was used, with spherical shape of the grains and size between 15-45µm. Fig. 2 illustrates the scanning of one contour, in order to study the influence of the input parameters (ET, PD and P), onto the output parameter, which is the surface roughness Ra.

Fig. 2. Powder of pure titanium TILOP 45 and the contour parameters

The SLM process was analyzed and a regression function needs to be found, as there cannot be established a precise mathematical dependence, between Ra and the independent parameters:

\[ Ra = f(ET, PD, P) \] (1)

Preliminary experimental research

The plan of the necessary preliminary experiments was made using the Design Expert software package version 9.01., which uses statistic techniques and allows a quick interaction. It helps the numeric and graphic optimization of the SLM manufacturing process, by taking into account the process factors and variables. The results could be visualized into 3D diagrams, presenting the response surface diagram.

The aim is to optimize the dependent parameter (Ra), which is influenced by the independent parameters. The Response Surface Methodology (RSM) was used, to obtain the empiric mathematical model, by using a mathematical combinations and statistical techniques.

Fig. 3. Preliminary experimental results
Previous experiments undertaken at DME showed the intervals in which the independent parameters could be modified, to produce a good surface quality of the SLM parts. The values of the parameters were within the following limits: ET: 80-120 [µs], PD: 10-30 [µm] and P: 100-140 [W].

The Design Expert software offers different possibilities to plan the experiments. The authors chose the central composition planning, second order, type $2^k$, where $k=3$ (k – the number of independent parameters). The software generated a table with 20 sets of experiments (illustrated in Fig. 3), where more independent parameters could be modified in the same time.

The following activities were undertaken, during the preliminary experiments: 3D modeling of the parts (in SolidWorks); Set-up the process parameters ET, PD and P (in REditor software), according to the matrix values of the experiments; SLM manufacturing of the samples; Roughness measurements.

Important characteristics of the titanium powder (TILOP45) used for the experiments are: low density (4.51g/cm$^3$), high melting point (1670°C), small dilatation coefficient, high electrical resistivity, small elasticity modulus and small thermal conductivity. Fig. 4 illustrates the SLM samples made onto the Realizer SLM 250 equipment at DME, to study the surface quality.

The surface roughness of these SLM parts was measured using the Mitutoyo equipment illustrated in Fig. 5, according to the ISO 1997 standard. The SLM parts were not post processed, before measuring the roughness, which was measured perpendicular onto the Z manufacturing axis.

The surfaces obtained by SLM have lines molten by the laser beam, small cavities and pores, as illustrated in Fig. 6 and 7, where the SEM images are presented at different magnification order.
The direction of the welding line can be observed for the outer contour, made using the parameters established within the Outer Boundary function. The thickness of the welded line is about 45-55 µm, as the layer thickness was 50 µm. It can be seen that there are no cracks on the surface, but there are some un-molten particles, or partially melted. If necessary, these particles could be removed by post processing the SLM parts. All the measurements were taken onto the vertical walls of the parts.

Modeling of the SLM process

The results of the preliminary experiments (presented in Fig. 5) were used to develop the mathematical model. These data could be approximated using different mathematical models. Once the suitable model of approximation was chose, we analyzed which values of the experiments are significant, some of them being neglected/eliminated from the regression equation which leads to the final shape of the model, presented in table 1.

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of squares</th>
<th>df</th>
<th>Media squares</th>
<th>Statistic F</th>
<th>Prob &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>82,66</td>
<td>8</td>
<td>10,33</td>
<td>21,04</td>
<td>0,0390</td>
</tr>
<tr>
<td>A - Expose Time</td>
<td>0,084</td>
<td>1</td>
<td>0,084</td>
<td>0,17</td>
<td>0,0487</td>
</tr>
<tr>
<td>B - Point Distance</td>
<td>1615</td>
<td>1</td>
<td>16,15</td>
<td>32,87</td>
<td>0,0001</td>
</tr>
<tr>
<td>C - Power</td>
<td>3,51</td>
<td>1</td>
<td>3,51</td>
<td>7,15</td>
<td>0,0217</td>
</tr>
<tr>
<td>AC</td>
<td>17,61</td>
<td>1</td>
<td>17,61</td>
<td>35,86</td>
<td>0,0010</td>
</tr>
<tr>
<td>BC</td>
<td>2,01</td>
<td>1</td>
<td>2,01</td>
<td>4,10</td>
<td>0,0680</td>
</tr>
<tr>
<td>A²</td>
<td>3,78</td>
<td>1</td>
<td>3,78</td>
<td>7,70</td>
<td>0,0181</td>
</tr>
<tr>
<td>B²</td>
<td>14,59</td>
<td>1</td>
<td>14,59</td>
<td>29,70</td>
<td>0,0002</td>
</tr>
<tr>
<td>C²</td>
<td>12,43</td>
<td>1</td>
<td>12,43</td>
<td>25,31</td>
<td>0,0004</td>
</tr>
<tr>
<td>Rest</td>
<td>5,40</td>
<td>11</td>
<td>0,49</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>88,07</td>
<td>19</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The empiric formula we determined, in order to calculate the Ra roughness of the parts made by SLM, is as follows:

\[
R_a(ET, PD, P) = c_1 + c_2 \cdot ET + c_3 \cdot PD + c_4 \cdot P + c_5 \cdot ET \cdot P + c_6 \cdot PD \cdot P + c_7 \cdot ET^2 + c_8 \cdot PD^2 + c_9 \cdot P^2
\] (2)

The coefficients of the mathematic model (c1,…,c9) are given in table 2 for SLM parts made out of titanium powder. New sets of coefficients need to be experimentally estimated for each new material, in order to apply this mathematical model for SLM parts made from other materials.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>c1</th>
<th>c2</th>
<th>c3</th>
<th>c4</th>
<th>c5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>146,71859</td>
<td>-9,2295E-01</td>
<td>-5,9698E-01</td>
<td>-1,4769</td>
<td>3,656E-03</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>c6</th>
<th>c7</th>
<th>c8</th>
<th>c9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>-2,3353E-03</td>
<td>2,4007E-03</td>
<td>1,911E-02</td>
<td>4,7213E-03</td>
</tr>
</tbody>
</table>

Using the Eq. 2 and the coefficients from table 2, the Ra values of the surface roughness of the titanium parts made by SLM could be easily calculated, using different process parameters.

Practical applications require establishing an optimal interval of values for each independent parameter, so that the Ra values of the SLM parts would be inside an imposed interval. That is why, a graphical optimization was done using the Eq. 2 and in this way, the relation between Ra and the independent parameters (ET, PD and P), could be quantified as the response surface diagrams, illustrated in Fig. 8 and Fig. 9.

The graphical optimization of the SLM process we made was obtained by representing the 3D surfaces as 2D curves, as cross sections at a constant value of the objective function. Based on these curves, the interval optimal parameters were graphically determined, in order to obtain particular
values of the Ra. Fig. 8 shows that for a constant PD (20 µm), the minimum Ra of 3.4 µm, can be obtained using the parameters ET 100 µs and P 120 W. The scanning speed defined by these values is 200 mm/s.

![Diagram of the Ra variation, with respect to ET and P, while PD is constant (PD=20µm)](image)

**Practical usage of this diagram is that, for example, if we need SLM parts with Ra lower than 4 µm, the laser power should be set between (107 W – 140 W) and the exposure time should be in the interval 75-120 µs.**

Fig. 9 illustrates the simultaneous influence of the laser power and scanning speed, onto the quality of the surface.

It can be observed that, a Ra roughness lower than 4 µm, the maximum theoretical value of the speed (352 mm/s), can be programmed by setting PD 30 µm, ET 85 µs and laser power 130 W.

![Ra roughness depending on ET and P, while PD is constant (30 µm)](image)

**Besides the small Ra roughness, it is important the efficiency of the SLM process, which means a high productivity. The optimal values of the SLM process parameters, which ensure a good surface quality (Ra smaller than 4 µm) and in the same time a high manufacturing speed, are as follows: PD=30 µm, ET = 87 µs and P = 133 W, resulting a 344 mm/s manufacturing speed of Outer Boundary. The Hatch parameter is programmed to scan the whole layer, as illustrated in Fig. 2.**

**Experimental testing of the mathematical model**

A new set of experiments was done, regarding the process parameters for the titanium powder. The Ra roughness values were calculated using the Eq. 1 and these values were compared with the values of the roughness measured onto the SLM parts made, using optimal process parameters. Table 3 presents the process parameters values, the calculated Ra roughness and the measured values of the Ra. The first set of process parameters are corresponding to the 4µm value of the Ra and to the maximum manufacturing speed of 344 mm/s. Table 3, that the maximum difference between the calculated values of Ra and the experimental values is below 0.5 µm.
Table 3. Experimental results versus theoretical calculated values of the Ra

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>87</td>
<td>30</td>
<td>133</td>
<td>4,1</td>
<td>3,9</td>
<td>+ 0,2</td>
<td>20,2</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>20</td>
<td>110</td>
<td>4,0</td>
<td>3,8</td>
<td>+ 0,2</td>
<td>19,2</td>
</tr>
<tr>
<td>3</td>
<td>120</td>
<td>20</td>
<td>120</td>
<td>4,3</td>
<td>4,0</td>
<td>+ 0,3</td>
<td>20,7</td>
</tr>
<tr>
<td>4</td>
<td>80</td>
<td>30</td>
<td>120</td>
<td>4,9</td>
<td>5,3</td>
<td>+ 0,4</td>
<td>28,2</td>
</tr>
<tr>
<td>5</td>
<td>120</td>
<td>10</td>
<td>135</td>
<td>9,6</td>
<td>9,2</td>
<td>+ 0,4</td>
<td>45,6</td>
</tr>
</tbody>
</table>

Conclusions

The RSM method was successfully used to optimize the SLM process, when using titanium powder. A new empiric mathematical model was obtained, to calculate the Ra surface roughness, as function of the independent parameters of the SLM process: ET, PD and P. Mathematical combinations and statistical techniques were used obtain the mathematical model (represented by Eq. 1), which was tested and validated by further experimental research. The maximum deviation of the experimental results was less than 10%, as compare to the theoretical estimations. Comparable results were reported by other researchers, such as A. Gebhardt [6] and J. A. Cherry [7].

This paper gives clear recommendations for the SLM process working with titanium powder, on how to obtain a small Ra and a high productivity of the process, in the same time. To obtain the Ra smaller than 4 µm, the values of the SLM parameters are recommended to be in the following intervals: PD: 20÷30 µm, ET: 84÷107 µs and the laser power P: 120÷135 W.

This research has been supported from the project PCCA 115/2014 “PECIFCO”.

References
