Influence of the Process Parameters on the Shape and Dimensions of the Parts Obtained by Selective Laser Sintering (SLS)

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Abstract. Selective laser sintering is an additive technology that uses the energy of a laser beam together with an additional heating source in order to generate the high enough temperatures for particle bonding. Due to the multitude of process parameters that have to be controlled during the process, inconsistencies in shape, size and mechanical properties of the parts occurs in all additive manufacturing technologies. The purpose of the paper was to quantify the influence of the part position along the front-back (Y) axis of the machine, on the thickness and cross section taper angle of parts. The material used in study was Alumide and the sinterization process was accomplished on Formiga P 100 machine. The idea of the study relay on experimental observations conducted along the time. These indicate that the geometry of the part is significantly influenced by the positioning of the models in the building plane. The statistic data processing prove that the parts are significantly different from the geometrical point of view when grows in different locations of the building plane.

1. Introduction

The additive technologies became wide spread both in industry and among hobbyist. Independently on the type of technology that is used, the accuracy of the parts represents a challenging research issue. The inconsistencies in shape, size and mechanical properties of the parts are associated with a series of technological parameters that are specific to each technology [1-7].

Galantucci et al approaches the analysis of dimensional performance of the parts obtained by mean of two additive systems that both use fused deposition modeling technique. Using a digital microscope they measure three orthogonal dimensions of the parts in order to establish the relationship between the technological factors and the parts dimensional error. The differences between the real and nominal specimen dimensions were in the range of 2-3 tenths of millimeters [8].

P.J. Nuñez et al analyze several elements of parts obtained by fused deposition modelling. They focus on dimensional precision, flatness error and surface texture. The purpose of the study was to establish the exact tolerance and surface finish that this process can offer. The poor dimensional control of the part was associated with physical contractions during curing. These lead to deviations in order of hundreds of millimeters for a certain layer thickness. An important observation was that decreasing the layer thickness to minimum, the deviations grows then times, in order of tenths of millimeters [9].

Tobias Lieneke et al proposes a methodical procedure designed to determine the dimensional tolerances of the parts obtained by FDM process. The tolerances were derived from measurements acquired using a micrometer screw. By comparing with ISO 286-1 standard, the tolerances of the manufactured parts reaches IT classes between 09 and 14. All the deviations are in the range of 2-3 tenths of millimeters [10].

Giovanni Moroni et al propose a new approach in establishing the tolerances of additive manufactured parts. The approach combines the current tolerancing practices with an X-ray scanning method. The volumetric representation is still based on voxels but it is enriched by the product and
manufacturing information. The volumetric representation of the measured points versus nominal geometric coordinates produces a confirmation of the correct tolerance field [11].

Goodridge R. D. et al concatenate some studies on the factors that influence the selection and selective laser sintering of the polymers. Factors like layer thickness, energy density, part orientation and placement, powder degradation and reuse, post build cooling rate, temperature distribution inside the machine were considered to influence the mechanical properties and geometry of the parts. One of the conclusions was the absence of commercial available system (machine) that solves the inconsistencies in dimensions and properties, caused by the uneven temperature distribution [12].

G. Berti et al conduct mechanical testing in order to characterize the composite PA- Al2O3, manufactured by selective laser sintering. After building a series of samples in different orientation respecting to the transversal axis of the machine they subject them to the mechanical testing. The samples present evident anisotropy in the growing direction (z-axis) and seem to be not sensitive to the sintering x and y directions at the room temperature. In addition, they conclude that the effect of sintering direction becomes more evident at higher temperatures [13].

This study underlines the geometrical differences of the parts according to the front-back (Y axis) direction of the machine. The idea of the study relay on the experimental results observed along the time, and which indicates that the parts that grows closer to the machine’s door, have better dimensional stability.

2. Materials and methods
Selective laser sintering is an additive technology that uses the energy of a laser beam in order to generate the high enough temperatures for particle bonding (figure 1). The parts were build on EOS Formiga P 100 machine, all in the same conditions, the single process variable being the location of the parts in the building environment (figure 2). By keeping all other process parameters constant (energy density, layer thickness, material, scaling factors, type of laser scanning, building and removal chambers temperatures, cooling conditions and so on), the differences in geometrical characteristics of the parts can be put on the part positioning in the building envelope.

![Figure 1. SLS Machine structure [14].](image1)

![Figure 2. Part positioning in building envelope.](image2)

The material used was Alumide. This is an EOS product that consists of homogeneous mechanical mixture of polyamide 12 (PA12) particles and aluminium whiskers. During sinterization process, the polyamide part of the mixture fuses together gripping inside the aluminium whiskers. The result of this
process is a still porous part but with a better density than the polyethylene alone. The presence of aluminium gives to the object a better rigidity and facilitates coatings and polishing. Beside these, better machinability, superior mechanical properties and more reliable dimensional accuracy can be encounter in alumide.

The sample part was designed in Solidworks 2013 according to the ASTM D638-14 standard. In the figure 3 and 4 the sample shape can be observed, together with the nominal rectangle cross section A-A and real cross section obtained on manufactured parts. Having different widths on button and top surfaces, the tapper angle can be calculated for the section. The full tapper angle \(2\alpha\) was computed (equations 1 and 2) based on \(W_1\) and \(W_2\) widths of the section and the height \(T\) of the section (figure 4), all measured in the cross sectional plane of the sample part.

\[
\tan \alpha = \frac{AB}{T} = \frac{(W_2 - W_1)}{2 \cdot \frac{1}{T}} \tag{1}
\]
\[
2\alpha = 2\text{atan} \left( \frac{W_2 - W_1}{2 \cdot T} \right) \tag{2}
\]

A total number of 15 parts were manufactured. The part distribution was on three layers. In the first building layer the parts were oriented along the X axis of the machine. In the second layer (5 mm on the top) the parts orientation was 45 degrees to the X axis while in the third layer the parts were oriented along the Y axis (90 deg to the X axis). Every layer contains 5 samples which run from position 1 to 5. The first position was always closer to the machine center while the fifth position was closed to the machine’s access door. The option of growing parts at different orientation was decide in order to eliminate the relation between the measurements and a certain part orientation.

The measurements were conducted using a digital caliper that has a 0.01 mm resolution. Nine sections were measured on each of the samples (figure 3), resulting 27 measurement values for every dimension (T, W1 and W2) at each sample position.

3. Results and discussion

Raw data of thickness and full tapper angle were presented in the figures 5 and 6. The thickness is a representation of measured data while the tapper angle is a computational value that takes into account both widths variables. Observing the data distribution on both graphs, for every part positioning, no evident tendency can be identified. Therefore, statistic data processing is required.
Figure 5. Raw data of thickness.

Figure 6. Raw data of full tapper angle.

For the 3D geometrical model the nominal values were: 4.20 mm for thickness and 0° for tapper angle, both constant. Before sending the 3D model to the machine this was scaled by the following coefficients: 2.3% for X and Y directions and 1.3% for Z. The scaling coefficients were applied for compensating the shrinkage that occurs during cooling phase, in order to obtain results as close as possible to the nominal dimensions.

The normal percentiles were computed using the thickness and tapper angle data of all sample parts. These graphs (figure 7 and 8) show a good data grouping around the mean (small standard deviation) and also a normal distribution. The percentiles of thickness indicate that 40% of the values are smaller than the nominal value 4.2 mm while all the other 60 % are larger. This may lead to the conclusion that the scaling factors used (X2.3%, Y2.3% and Z1.3%) are overestimating the shrinkage. On the other hand, there is no percentage of parts that possessed zero degree of tapper angle.

Figure 7. Normal percentiles of thickness.

Figure 8. Normal percentiles of tapper angle.

In order to establish the variation of the thickness and tapper angle with the position in the building plane, the data were sorted on five series: Pos. 1 to 5. Under the position 1 data series the nine measurements of three parts can be found. The results were averaged and the standard deviation was
computed. By following the same protocol for all the five positions, the data were processed. The graphic representation of these can be found in the figures 9 and 10.

![Figure 9. Bar chart and regression for thickness.](image1)

![Figure 10. Bar chart and regression for tapper angle.](image2)

The polynomial 4\textsuperscript{th} order regression lines are fitting the data with an $R^2 = 1$. The polynomial regression is accepted in this case because the edge of the intervals corresponds to parts that grown close to the physical border of the building envelope.

By analyzing the data distribution and the standardized residuals (not presented in the paper) for W1, W2 and T dimensions, a Gaussian data distribution was confirmed.

The statistical difference of thickness and tapper angle between the first and the fifth positions of the parts was put in evidence by the probability test. The null hypothesis $H_0$ was defined: there is no significant difference in parts thickness/tapper angle recorded for the positions 1 and 5. The alternative hypothesis $H_a$ was defined: the thickness/tapper angle difference is significant.

The results of $p$ values: 0.198866 for thickness and 0.166779 for tapper angle are both higher than 0.05 and therefore $H_0$ is rejected and the alternative hypothesis $H_a$ is accepted.

4. Conclusions
This study underlines the geometrical differences of the alumide parts obtained by selective laser sintering according to the front-back (Y axis) direction of the P100 Formiga machine. The results represent a case study and the generalization to all types of SLS machines have to be done with cautious.

The 40\% of thickness are smaller than the nominal 4.2 mm value while all the other 60 \% are larger.

Both thickness and tapper angle of the parts are significantly influenced by the front-back (Y axis) positioning of the models in the building plane, as statistics indicate. Also, the two parameters exhibit a reverse effect.

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