A procedure for assessing geometrical accuracy of selective laser melting processes with standard parts

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Abstract. The assessment of the geometrical accuracy of an additive manufacturing process is crucial to evaluate its capability to produce parts within specification limits. A standardized procedure for the accuracy evaluation of SLM processes with standard parts is proposed. The procedure includes recommendations for manufacturing, measurement and statistical evaluation. Process repeatability and bias are defined as characteristic accuracy indices. A case study was carried out in which two systems were compared. Repeatability was similar for both systems. Not negligible bias was detected but there was no evidence of significant difference between biases of both systems.

1. Introduction

The title Selective Laser Melting (SLM) is an additive manufacturing processes that consists in scanning a laser beam over a thin layer of powder that is previously distributed over a substrate, making the powder particles to melt and weld to each other and to the underlying layer. This process is repeated layer by layer to form the final geometry of the part. Main strength of this process is the capability of manufacturing complex metallic parts. As with most additive manufacturing processes, geometrical accuracy of the produced parts is still a limiting factor. Accuracy evaluation is therefore critical in circumstances such as capability assessment, acceptance tests, periodic verification and performance benchmarking.

The concept of manufacturing and measuring standard parts to assess the accuracy of a manufacturing process is not new and is common practice for CNC machining processes [1,2]. These parts feature a number of geometries that are sensitive to errors that are typical to the manufacturing process. Developments for additive manufacturing are more recent [3,4,5].

In order to be accepted by both equipment manufacturers and users, an accuracy evaluation process has to be standardized or at least very well specified. Apart from the geometry of the standard part, this specification should also include details on manufacturing conditions, measurement process and statistical evaluation criteria. In this work we propose a complete procedure for the evaluation of the geometrical accuracy of SLM including these aspects. The procedure will be demonstrated for parts manufactured from a Titanium alloy, but is applicable to other metallic materials.
2. Performance evaluation procedure
The proposed procedure is summarized in the flow-chart in Figure 1. The basic concept is to manufacture, measure and statically evaluate the results of a set of at least three parts. The manufacturing conditions must follow the recommendations of the equipment manufacturer. Measurement strategy is standardized for each feature type. Measurement results are used to calculate repeatability (process variability) and bias (systematic process error) for groups of geometrical features of the standard part. These results can be applied to evaluate a given manufacturing process or to compare different processes. The geometry of the proposed standard part and each step of the evaluation procedure will be outlined in sections 2.1 to 2.4.

![Flow-chart of performance evaluation procedure](image)

Figure 1: Performance evaluation procedure.

2.1. Geometry of the standard part
A systematic product development method was used to design the standard part. The most important criterium is that the geometrical features should be sensible to typical geometrical errors of SLM processes and, on the other hand, that they represent geometries that are typical for this manufacturing process. Starting from these global requirements, and based on an extensive literature research, a product specification was generated. Some of the specific requirements that we considered are: scalable geometry, low manufacturing time and cost, features easily measurable with standard tactile coordinate measuring machines (CMM), geometrical features on both vertical and lateral planes and internal and external features of different sizes.

A number of possible options to fulfill these requirements were generated and the final solutions selected using a decision matrix. The final geometry is depicted in Figure 2. Seven feature groups (FG 1 to FG 7) were included to evaluate different aspects of the SLM process. In our test we produced parts with overall dimensions 40 mm x 40 mm x 17 mm, but the geometry may be scaled to fit the working space of each individual equipment.
2.2. Specification of the manufacturing process

Generally speaking, recommendations of the manufacturer of the SLM system should be followed. Furthermore, it is important to document all process related data, such as material specification, scanning speed, layer width, laser power, and laser focal point diameter. The choice of the parameters should also be consistent. For instance, if systems of different manufacturers are being compared, parameters should be selected in a way that the manufacturing time is approximately the same for each system, since scanning speed may significantly influence geometrical accuracy.

2.3. Specification of the measurement process

A calibrated tactile coordinate measuring machine (CMM) is used to measure all features. The uncertainty of the measurement process should be sufficiently low to not significantly contaminate the analysis of the production process with the variability of the measurement process. Information on task-specific uncertainty of CMM measurement is rarely available. Equation 1 defines an acceptable criterion for deciding whether a CMM is suited. The maximum permissible length measurement error ($MPE_E$) is one of the main accuracy specifications of a CMM and is available in the equipment data sheet. The definition of the process repeatability $Re$ will be is outlined in the next section. A value for the expected repeatability may be used.

$$MPE_E \leq \frac{Re}{5}$$

(1)

We propose to standardize the measurement process in order to avoid conflicts in results generated with different strategies. Each feature is measured by probing single points (not scanning). The probing element (sphere) of the probing stylus should be sufficiently small to reach the smallest hole of part but the probe should also be robust, i.e., the shaft diameter should be as large as possible.

Part alignment is depicted in Figure 3. Primary and secondary reference planes should be probed at least at four evenly distributed points. Tertiary reference circle should also be defined with at least four points.

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Figure 2: Standard part geometry.

Figure 3: Part alignment
Evaluation strategy as well as number and distribution of the probing points for each feature group should follow recommendations in Table 1.

| Feature group | Measurement strategy |
|---------------|----------------------|
| 1             | Circle diameter, 4 points, evenly distributed, 1 mm from surface |
| 2             | Circle diameter, 4 points, evenly distributed, 1 mm from surface |
| 3             | Circle diameter, 4 points, evenly distributed, 1 mm from cylinder start |
| 4             | $x$-coordinate, 1 point in the middle of the step |
| 5             | Difference in $y$-coordinate of two points, probing 1 mm from topside surface |
| 6             | Difference in $y$-coordinate of two points, probing 1 mm from topside surface |
| 7             | Differences in $x$ or $y$ coordinate of two points, probing in the centre of surface at 6 mm from topside |

2.4. Specification of the measurement process

The goal of the statistical evaluation is to generate significant characteristic indices to quantify the process variability as well as process bias for each feature group.

The characteristic value for the process variability on manufacturing a specific feature type is the process repeatability $Re$. The steps to calculate $Re$ for a feature group are:

a) Calculate errors according to Equation 2, where: $e_{i,j}$ is the error of feature $i$ of part $j$, $x_{i,j}$ is the measurement result of feature $i$ of part $j$ and $x_{\text{nom},i}$ is the nominal value of feature $i$;

$$e_{i,j} = x_{i,j} - x_{\text{nom},i}$$  \hspace{1cm} (2)

b) Calculate the mean error of each feature according to Equation 3, where $n$ is the number of parts;

$$\bar{e}_i = \frac{\sum_{j=1}^{n} e_{i,j}}{n}$$  \hspace{1cm} (3)

c) Calculate the standard deviation of feature $i$ according to Equation 4;

$$s_i = \sqrt{\frac{\sum_{j=1}^{n} (e_{i,j} - \bar{e}_i)^2}{n - 1}}$$  \hspace{1cm} (4)

d) Calculate the pooled standard deviation of the feature group according to Equation 5, where $m$ is the number of features in the feature group;

$$s_p = \sqrt{\frac{\sum_{i=1}^{m} s_i^2}{m}}$$  \hspace{1cm} (5)

e) Calculate the degrees of freedom (Equation 6);

$$df = m(n - 1)$$  \hspace{1cm} (6)

f) Calculate the process repeatability according to Equation 7, where $t_{df}$ is the Student’s distribution coefficient for a coverage probability of 95% and $df$ degrees of freedom.

$$Re = t_{df} \cdot s_p$$  \hspace{1cm} (7)
The use of the pooled standard deviation $s_p$ instead of the overall standard deviation of errors $e$ aims at eliminating the variability related to size-dependent effects. It is acceptable to use $s_p$ as long as the variances of the features within a group do not significantly differ from each other. Appropriate statistical tests should be conducted to confirm the validity of this assumption if standard deviations $s_i$ significantly differ from each other.

Process bias $b$ is defined in terms of a confidence interval. The procedure to determine $b$ of a feature group is:

a) Calculate overall mean (Equation 8);
\[ \bar{e} = \frac{\sum_{i=1}^{m} e_i}{m} \tag{8} \]

b) Calculate overall standard deviation (Equation 9);
\[ s = \sqrt{\frac{\sum_{j=1}^{n}(e_{i,j} - \bar{e})^2}{n \cdot m - 1}} \tag{9} \]

c) Calculate degrees of freedom (Equation 10);
\[ df = m \cdot n - 1 \tag{10} \]

d) Calculate bias confidence interval according to equation 11, where $t_{df}$ is the Student’s Distribution coefficient for a coverage probability of 95%.
\[ b = \bar{e} \pm t_{df} \cdot \frac{s}{\sqrt{n \cdot m}} \tag{11} \]

3. Case Study
We carried out a case study to test the procedure. Two different SLM systems – A and B – were evaluated. We produced three parts with each system. Figure 4 depictures three parts produced with equipment A.

![Figure 4: Parts produced with equipment A.](image)

Process parameters were selected according to the specifications of the system manufacturers and are documented in Table 2. The material is Ti6Al4V for all parts.
Table 2: Process parameters.

| Parameter          | Equipment A | Equipment B |
|--------------------|-------------|-------------|
| Laser power        | 350 W       | 200 W       |
| Manufacturing speed | 1400 mm/s   | 1250 mm/s   |
| Hatch spacing      | 0.120 mm    | 0.105 mm    |
| Layer thickness    | 0.03 mm     | 0.03 mm     |
| Focal diameter     | 0.07 mm     | 0.15 mm     |
| Platform temperature | 200°C     | N/A         |
| Material           | Ti6Al4V     | Ti6Al4V     |

All the features of the parts were measured in a metrology laboratory with a high accuracy CMM according to the standardized measuring strategy. Figure 5 shows the individual results for feature group FG1 – topside internal diameters and FG 2 – lateral internal diameters, FG 5 – wall thickness and FG 6 – keyway width. The values circled in red are outliers. The causes for these outliers could not be identified. These values were eliminated from the analysis, since they would significantly influence the values for repeatability and bias. Unfortunately, we were not able to evaluate the remaining feature groups due to lack of availability of the CMM.
The values for the process repeatability (equation 7) and the confidence intervals for process bias (equation 11) are summarized in Table 3. Repeatability is in the same order of magnitude for both systems for all feature groups. Figure 6 compares biases of equipment A and B. It is interesting to note that all bias values are statistically significant, since the confidence intervals do not cover the value “0”. On the other hand, the confidence intervals of both systems overlap for all feature groups, meaning that there is no significant difference between bias values of both systems. This is evidence that biases are related factors that are not equipment-specific.

Table 3. Process repeatability and bias.

| Feature group | Repeatability ($R_e$) [mm] | Bias ($b$) [mm] |
|---------------|-----------------------------|-----------------|
| FG 1          | Equipment A: 0.028          | Equipment B: 0.022 | Equipment A: -0.104±0.009 | Equipment B: -0.117±0.007 |
| FG 2          | Equipment A: 0.054          | Equipment B: 0.060 | Equipment A: -0.259±0.024 | Equipment B: -0.272±0.042 |
| FG 3          | Equipment A: 0.047          | Equipment B: 0.028 | Equipment A: 0.051±0.012 | Equipment B: 0.067±0.013 |
| FG 5          | Equipment A: 0.028          | Equipment B: 0.022 | Equipment A: -0.075±0.016 | Equipment B: -0.071±0.013 |
4. Discussion and Conclusions

The outliers detected in the case study proved that it is important to not only calculate global values for process repeatability and bias but also to analyze individual results. Also, biases that are not related to the specific equipment could only be identified based on the analysis of the bias confidence intervals, thus demonstrating the effectiveness of the proposed statistical evaluation.

The outliers identified in FG 5 and FG 6 may be related to the measurement strategy, since these distances were determined by measuring one single point on each surface. Probing several points on each surface and calculating the distance between average coordinates would probably result in more stable results. The holes should also be probed with more than four points to increase redundancy.

In this work we focused on SLM processes. Nonetheless, in principle, the proposed procedure is applicable to other additive manufacturing processes. It may be eventually necessary to adapt the geometry of the standard part to specific characteristics of each process.

With this research we hope to contribute to the efforts of producing national and international standards for the performance evaluation of additive manufacturing processes. However, we also understand that it is an ongoing process and that significant discussion and cooperation between system manufacturers, users, standardization organizations and academia is still required.

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