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Development of a novel benchmark artifact for Additive Manufacturing processes

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Abstract
Additive Manufacturing (AM) allows generation of geometrically complex parts which cannot be obtained by conventional processes (machining, forging, casting *e.g.*). It also enables production of near net shape parts requiring few finishing operations before use (roughness reduction *e.g.*). Mastering geometrical and dimensional accuracy of additively manufactured parts is then mandatory to ensure their functionality. In conventional processes, dimensional accuracy of different machines or process conditions (hard machining vs super finishing *e.g.*) can be objectively compared using the International Tolerance (IT) grades defined by the International Standard Organization (ISO) in ISO 286-1 GPS standard (Geometrical Product Specifications). Required geometrical accuracy can be specified using ISO 1101. In the specific case of blank produced by machining operations, ISO 2768-1 is often used for dimensional tolerancing and ISO 2768-2 for geometrical tolerancing. In the case of Additive Manufacturing, neither dimensional and geometrical tolerancing standard nor benchmarking method standard exist. The solution proposed by many authors is to develop their own benchmark artifact to evaluate the dimensional and geometrical accuracy of their machine, their minimal achievable detail size as well as their capability to replicate a given shape within a given International Tolerance grade. This article aims to make a review of the existing benchmark artifacts and to summarize the main requirements chosen by authors. From this state of the art, a new benchmark artifact is proposed by adapting an existing one to fulfil its missing characteristics. Measurements possibilities in terms of dimensions are enumerated and organized using ISO 286 dimensional intervals as presented in the literature. Geometrical evaluation possibilities are also listed and enumerated. It is then applied to a part obtained by Fused Deposition Modelling (FDM).

Additive manufacturing, benchmarking, dimensional accuracy, FDM, geometrical accuracy, IT grades, performance evaluation

1. Introduction

In conventional processes (milling *e.g.*), standards describe accuracy evaluation methods as well as values of dimensional (ISO 286-1 GPS *e.g.*) and geometrical tolerances (ISO 1101 *e.g.*). This allows the user to foresee adjustments between parts in assemblies and to assess the possibility to manufacture a part with a given process. Despite the unlock of design possibilities and production of near net shape parts, additive manufacturing (AM) suffers from lack of standard in accuracy evaluation and tolerancing [1,2].

Solution proposed by many authors is to use a benchmark artifact allowing dimensional and geometrical evaluation of additively manufactured parts [2–6]. Three main classes can be established according to their main goals [1,6]: geometrical benchmarks, benchmarks to assess mechanical properties and process benchmarks [1]. In this classification, it is the first category that has been chosen since the main objectives of these artifacts are to characterize quantitatively the dimensional and geometrical accuracy, spatial repeatability (the ability to reproduce a given geometry at different places on the buildplate) and minimum achievable details size [6].

Up to now, there is no standard for AM benchmark parts [1,2]. ASTM F42 working group and ISO TC261 are working on this subject [3,5]. Moylan *et al.* [3] propose a strategy to establish benchmark artifacts that can be printed to assess the performances of machines belonging to each of the seven AM process categories defined by ASTM F2792-12a. As all machines exhibit different building volume, there is no possible universal benchmark artifact [1]. It has to be adapted to the machine which will print it and has to fullfill common requirements [3].

In this context, this article aims to propose a modified version of an existing artifact and to evaluate accuracy of an AM printer in terms of dimensions and geometry. Direct output of these results is manufacturability determination of a given part.

2. Methodology

First a literature review is conducted in order to list main requirements chosen by authors to design benchmark artifacts. Then, an existing benchmark artifact is selected and modified in order to fulfil its missing characteristics. Afterwards, evaluation of dimensional and geometrical measurements possibilities is performed in order to verify the part compliance with its main goals. Part design is subsequently printed five times. Finally, its dimensional and geometrical characteristics are evaluated using a coordinate measuring machine (CMM).

3. Literature review

A literature review has been carried out to summarize the common design requirements proposed by different authors.

First, benchmark part size has to enable testing of all the building area and characterize the influence of details position on their dimensional and geometrical accuracy [1,6]. The choice of a part exhibiting a smaller size than the buildplate can be made. In this case, the part has to be reproduced at different places of the buildplate [6]. Part volume has to be kept as small as possible since some AM processes exhibit high feedstock and process costs as well as slow building rates (Ti6Al4V printing by Electron Beam Melting *e.g.*) [1,2,4,6]. Benchmark artifact has to be provided with a wide number of details of different sizes [1–3,5,6] in order to cover the dimensional size ranges detailed in

ISO 286-1 [7]. Simple inward and outward details have to be selected (cylinders, spheres, rectangular parallelepiped bosses…) [2,3,5] in order to allow fast measurements. These simple geometries are used to determine geometrical characteristics: flatness, straightness, parallelism, perpendicularity, cylindricity, angularity, position and profile [6]. Moreover, specific details required for the end function of the part should be added to the benchmark (lattice *e.g.* in the case of additive manufacturing of osseous regenerative scaffolds) [1–3]. Dedicated orientations with respect to the cartesian axes of the machine should be given to the details in order to emphasize axes inherent deviations (misalignments, wear, *e.g.*) [1,3,6,8]. Details allowing determination of the machine minimum achievable size for a given geometry have to be included on the part [3,6,8]. Furthermore, details must be printable without support [3] and contain slope to highlight staircase effect [8]. Overhang features are required to underline their feasibility without support [8]. Finally, the base of the benchmark part has to be sufficiently thick (> 5 mm) to avoid warping effect during fabrication [5]. Kruth *et al.* [8] recommend horizontal low thickness flat surface and sharp edges (14° to 45° angles) to respectively show warping sensibility of the process and defects coming from high heat at angle tips. These last two features were not included in the part since they can influence other details accuracy.

4. Results

4.1 Modification of an existing benchmark design

Based on the literature review, an existing benchmark design has been selected. The choice has been made on the benchmark artifact proposed by Moylan *et al.* [3] since it is the one that fulfils the highest number of requirements found in literature. It has then be modified to comply with the general requirements presented in section 3. Final design is presented in figure 1 and modifications which were made are highlighted in green.

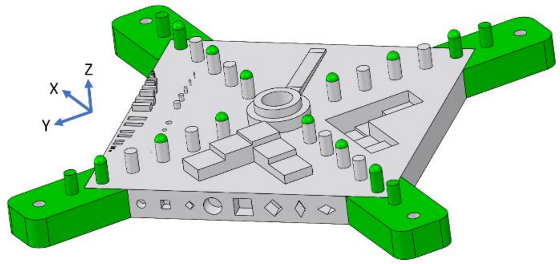

Figure 1. Final design based on Moylan *et al.* part [3] (modifications introduced in this study are shown in green).

Size of the benchmark has been adapted to use the maximum building volume available in an Ultimaker 2+ Fused Deposition Modelling (FDM) printer (223 mm x 223 mm x 205 mm according to X, Y and Z axes). For this purpose, the initial diamond shape has been extended by four arms fitted with rounded edges (5 mm radius). Extreme distance between arms stands at 190 mm. Small cylinders number has been increased from 16 to 24 to cover the available space. Hemispheres have been added on the half of small cylinders top surfaces. The rest of the geometry is the same as described by Moylan *et al.* [3].

4.2 Analysis of the possible measurements

Possibilities of dimensional measurements have been listed according to ISO 286-1 standard [7] dimensional size ranges. They are shown in figure 2. Repartition across dimensions from 1 mm to 250 mm is homogeneous except for dimensional size ranges 10-18 mm, 120-180 mm and 180-250 mm categories. In total, 302 dimensional measurements can be performed on each part.

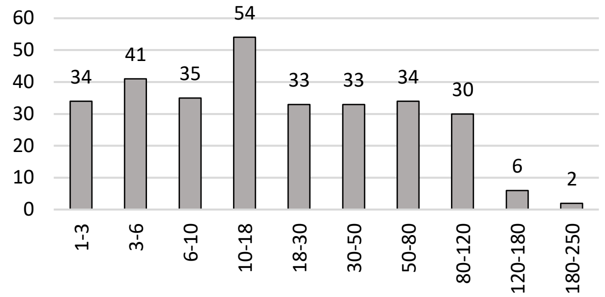

Figure 2. Number of possible dimensional measurements according to ISO 286-1 dimensional size ranges (in mm).

Measurements repartition with respect to the printing machine cartesian axes is shown in Table 1. Dimensional deviations can be related directly to one of the machine cartesian axes. *Other* category takes into account measurements depending on more than one cartesian axis (diameter of cylinders *e.g.* depends on X and Y axes). As shown in Table 1, details of size < 10 mm are in majority along Z axis while details between 10 mm and 120 mm are in majority belonging to the X or Y axes categories.

Table 1 Repartition of dimensional measurements across machine axes according to ISO286-1 dimensional size ranges (in mm).

Above	Up to and including	X	Y	Z	Other
1	3	0	0	22	12
3	6	0	0	13	28
6	10	2	2	30	1
10	18	12	12	29	1
18	30	16	16	0	1
30	50	17	16	0	0
50	80	17	17	0	0
80	120	14	14	0	2
120	180	3	3	0	0
180	250	1	1	0	0

Geometrical measurements possibilities have also been listed and are shown in figure 3. Their total number stands at 280. Only a selection of the measurable surfaces were chosen in order to guarantee fast measuring of the part as well as sufficient information about its geometrical details. As depicted in figure 3, position measurement is most numerous. This comes from the 24 cylinders covering the part top surface. Horizontal plane category refers to planes normal to Z axis while vertical plane categories encompass planes normal either to X or to Y axes of the machine.

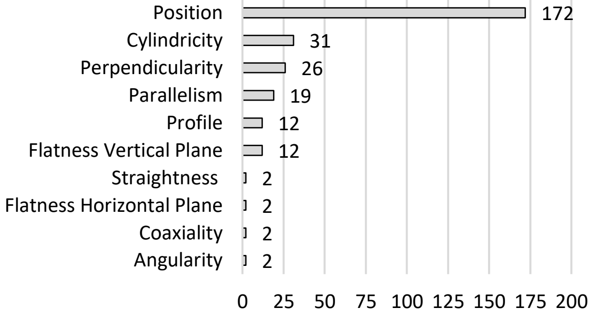

Figure 3. Possibilities of geometrical measurements.

Machine cartesian axes repartition of geometrical measurements possibilities were listed too and are shown in table 2. Repartition of measurements according to X and Y axes is uniform. Flatness of horizontal plane and parallelism according to Z axis are less represented than other categories since only the top surface was used to perform these measurements. Straightness is the less represented category in the table and is measured using the axes alignements of small cylinders with respect to X and Y axes.

Table 2 Repartition of geometrical measurements across machine axes.

Geometrical Measurement	X	Y	Z	Other
Angularity			2	
Coaxiality				2
Cylindricity				31
Flatness Horizontal Plane			2	
Flatness Vertical Plane	4	4		4
Parallelism	7	7	2	3
Perpendicularity				26
Position	71	70		31
Profile				12
Straightness	1	1		

4.3 Manufacturing of the modified part design

Five benchmark artifacts have been printed in PLA on an Ultimaker 2+ FDM machine using a filament diameter of 2.85 mm. Nozzle diameter of 0.25 mm has been selected with a layer height of 0.06 mm. Printing speed was reduced to 24 mm/s for the first layers and a brim of 12 mm has been chosen to enhance part adherence to the buildplate. Printing speed for other layers was set at 30 mm/s. Infill density stands at 20 % with a cubic strategy. Bed and nozzle temperatures were set at default settings respectively at 60 °C and 200 °C. Total build time for each part took 48 h. One of the printed part is depicted in figure 4 along with the cartesian axes orientations and the printing zone of the machine.

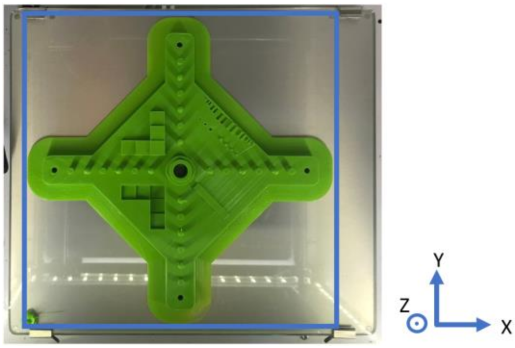

Figure 4. Final printed part (printing zone depicted in blue).

4.4 Parts measurements

The five parts were measured using a CMM Wenzel LH54 equipped with a Renishaw head PH10M and a Renishaw TP20 spherical probe diameter of 2.5 mm and 2.0 mm. Measurement uncertainty (in µm) for a given measured length L (in mm) = 3+L/300 for X and Y axes and = 3.5+L/300 for Z axis. These are negligible with respect to standard deviation of the measurements. All planes were measured using 6 points except for top surface which was measured with 20 points in order to have a better reprensentation of its flatness deviation. All cylinders were measured using 8 points distributed over two circles. Hemispheric top of small cylinders were evaluated using 10 points: 1 on the summit and 9 distributed over two circles. The first of the two circles starting from the top of the hemisphere encompasses four points while the second contains five. Distance between the part top surface and small cylinders (4 mm diameter) top surfaces were measured with one point. The parts were measured after removal from the buildplate and after cut out of the brim by hand. Indeed, these operations deteriorate the flatness of part bottom surface and lead to deformations. However, parts have been removed from the buildplate since it is needed before their assembly *e.g.*

4.5 Dimensional evaluations of the part

ISO IT grade for each dimensional measurement was evaluated following the method presented in ISO286-1:1988 (Minetola et al. presented results according to [4,5] but for another part design and different printers). All the following equations are related to dimensions inferior or equal to 500 mm and IT from 5 to 18. This method uses a standard tolerance factor i (in µm) which is computed for each dimensional size range of the ISO 286-1 according to equation (1). D is the geometrical average of the two extreme dimensions composing dimensional size range (equation (2)). For example i = 1.083 µm for 10-18 mm ISO dimensional size range ($D1$ = 10 mm and $D2$ = 18 mm) and D = 13.416 mm. Deviation of each part dimension is then compared to the standard tolerance factor i of the dimensional size range to which belongs the dimension. The quotient of both quantities is called number of tolerance units n (adim) and can be computed according to equation (3) where Dn (in mm) is the nominal dimension and Dm (in mm) its measurement.

$$i = 0.45 \cdot \sqrt[3]{D} + 0.001 \cdot D \quad (1)$$
$$D = \sqrt{D1 \cdot D2} \quad (2)$$
$$n = (1000 \cdot |Dn - Dm|) / i \quad (3)$$

ISO286-1 gives the maximum allowed value of n for each IT grade (IT 15 requires a number of tolerance units inferior to 640 *e.g.*). For example, if a measurement of a nominal distance of 100 mm is performed and equals 99.049 mm, the computed n is equal to 437.644 and leads to an IT15 ($D1$ = 80 mm, $D2$ = 120 mm, D = 97.980 mm and i = 2.173 µm).

Same calculations have been conducted for all dimensions of the part (distance between planes and radius of cylinders, holes and hemispheres). Figure 5 gives the final result for the five parts according to the different cartesian axes of the printing machine. Standard deviation σ has been computed for each set of datas and 2σ is taken as error bars. As before, the category *Other* takes into account dimensions which belong to more than one axes.

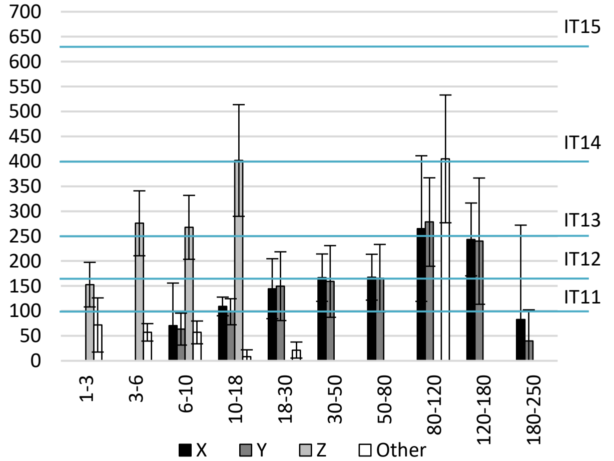

Figure 5. Number of tolerance unit n (adim) for the different ISO286-1 dimensional size ranges (in mm).

As depicted in figure 5, details of dimension < 10 mm fit into IT14. Features between 10 mm and 18 mm according to Z axis are less accurate and respect IT15. 6 mm to 80 mm details according to X and Y axes lay in IT13. Only items from 80 mm to 120 mm according to Y axis respect IT14, other features according to X axis are less accurate and fit into IT15. Details from 120 mm to 180 mm according to X and Y axes show the same trend and lay in IT14. Finally, part dimensions superior to 180 mm tend to respect IT14. This last result has to be balanced with the low number of measurements available on the part (only 2). Consequently, the graph shows that the Ultimaker 2+ used can overall satisfies IT15 across all dimensional size ranges.

In terms of dispersion of measurements across the different parts, it is the categories of dimensions of 10 mm to 18 mm parallel to Z axis and more globally the dimensions over 80 mm for all axes that show the largest values of standard deviations. These deviations are directly related to deformations occurring after removing the part from the buildplate due to residual stresses [1]. Modifying the proposed benchmark in order to decrease deformations can be a solution to this issue.

4.6 Geometrical evaluations of the part

Geometrical details positions (plans, cylinders, hemispheres) have been recorded during part measurement. This evaluation allows determining several geometrical measurements. Indeed, plans enable determination of angularity, flatness, parallelism and perpendicularity characteristics of the part. Straightness, cylindricity and coaxiality have been evaluated thanks to the cylinders arranged on part top surface. Finally, surface profile deviations have been characterized using the hemispheric details added on top of cylinders. Based on the obtained measurement results, graphs such as figure 6 can be established. This figure shows the parts straightness deviations according to X and Y machine axes. These measurements were acquired by extracting the positions of the intersection between each cylinder main axis and the part top surface. The resulting points were then processed to establish straightness deviation.

Same behaviour according to X and Y machine axes can be seen as presented by figure 6. Average straightness deviation reaches 0.022 mm for both axes while standard deviation σ stands at 0.006 mm. 2σ is taken as error bar. As for dimensional evaluations, relatively high values of σ are linked directly to the deformations arising when the part is detached from buildplate.

It should be noted that the values of straightness deviation were obtained along two 150 mm long lines. The value of 0.022 mm is relatively low compared to standard straightness deviation values which can be found in ISO2768-2:1989 [9]. Indeed, this standard requires straightness deviation inferior to 0.200 mm for dimensions between 100 mm and 300 mm (H tolerance class). ISO2768-2:1989 is indicated for subtractive manufacturing process but can be used also to give general values for other manufacturing processes.

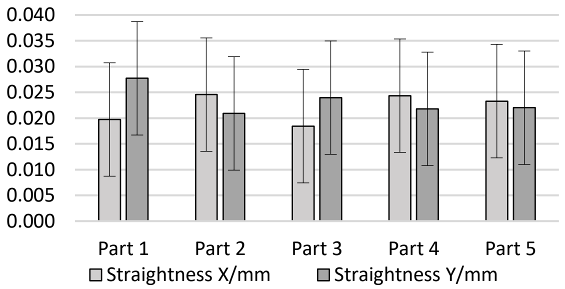

Figure 6. Straightness deviations according to X and Y axes.

5. Summary

This paper presents a modified benchmark artifact for additive manufacturing printers. Literature review allowed the collection of general requirements used by authors to establish benchmark artifact. An existing benchmark has then been selected and modified to fulfil the gathered requirements. Dimensional and geometrical measurements possibilities were assessed and the part has been printed five times. Measurements were then performed to evaluate the part dimensional and geometrical accuracy. These allow the user to foresee the manufacturability of a given part geometry with the studied printer.

6. Conclusions

Modified benchmark artifact overcomes limitations of the part proposed by Moylan *et al.* [3]. Indeed, the proposed artifact exploits more space of the available builplate surface, exhibits higher number of small cylinders and enables profile deviation measurements with the added hemispheres. 302 dimensional and 280 geometrical measurements can be performed on the part. 48 h are needed to print it with an Ultimaker 2+ with settings selected to maximize printer accuracy. ISO286-1:1988 method has been used to dimensionally characterize the part and determine its achievable ISO IT grades according to the dimension size ranges presented in the standard. Results show that the printer is able to reproduce parts details with dimensions between 1 mm and 80 mm within IT15 according to Z axis and within IT13 according to X and Y axes. Finally, geometrical evaluations have also been conducted and average straightness deviation stands at 0.022 mm for X and Y axes (straightness according to Z axis was not evaluated).

7. Future work

The chosen design showed accuracy limitations according to Z axis due to deformations occurring after removal of the part from the buildplate. Design modifications to decrease these deformations are required. Finally, process capability has not been determined but can be of major interest for industrial applications. This assessment is a perspective for this work.

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