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Determining the dimensional accuracy limits of laser sintered PA12-parts: from artefact design to dimensional characterization by X-Ray Computed Tomography

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Abstract
Laser sintering of polymers is increasingly used to produce functional parts with complex designs. These complex geometries often contain many features having different sizes and orientations, which are difficult to manufacture with the required dimensions and tolerances. In fact, both the slicing process, which discretizes the part into process-layers, and the local processing conditions determined by feature's size and scanning strategy, have an influence on the local dimensions. Although these are known problems, the magnitude of the effect caused by the different factors is not yet clear, especially when the feature's size gets closer to the resolution limits of the process. Being able to quantify the local dimensional deviations connected with both slicing parameters and local processing conditions, would allow to define compensation strategies. In this work we present a new design for a test artefact, which contains small holes and slots having different sizes and orientations. These features are placed in both horizontal and vertical walls, having a range of 4 different wall thicknesses, for a total of 376 different combinations. Several scanning strategies have been tested, in order to assess the influence of the process parameters. X-ray Computed Tomography is used to measure the dimension of each feature of the test artefact, allowing a complete overview of the influence of the different factors on the local dimensional deviations.

Keywords: Dimensional accuracy, Laser sintering, X-ray Computed Tomography

1. Introduction

Laser Sintering (LS) is a powder based Additive Manufacturing (AM) technique which uses a laser to locally melt powdered material layer by layer to form a solid part. In the past, this technology was mainly used for rapid prototyping, but is now increasingly used to create functional parts [1-2]. LS, like other AM techniques, has the benefit to be able to produce freeform complex structures, which are not manufacturable by traditional manufacturing technologies. LS users are increasingly making use of this design freedom to produce parts with geometries tailored for their applications. These complex geometries often contain many features having different sizes and orientations, which are difficult to manufacture with the required dimensions and tolerances. In fact, both the slicing process, which discretizes the part into process-layers, and the local processing conditions determined by feature's size and scanning strategy, have an influence on the local dimensions [3]. Being able to quantify dimensional deviations from the design is important, in order to be able to take them into account during the design phase and, possibly, define way to compensate for it. Several test artefacts have been designed, in order to quantify both the dimensional accuracy of the process and the capabilities of the machine. Moylan et al. [4] reviewed the artefacts available for AM process characterization and proposed a new artefact design for standardization. However, even though different AM processes have in common their layer-based manufacturing approach, they often show a different dimensional accuracy, which are specifically linked to a certain process-material combination. For this reason, a proper process-material characterization regarding the dimensional accuracy would require a dedicated artefact design, specifically addressing the process limitations. Seepersad et al. [5] investigated the printability and resulting dimensional accuracy of different features typically present on LS-PA12 parts processed on a 3D Systems Vanguard machine. Sippel [6] previously performed a similar work on LS-PA12 parts printed on an EOS P390 machine. These works helped to point out the dimensional deviations, induced by intrinsic process limitations, helping to define design rules for LS-PA12 parts. However, these works were limited to a single set of process parameters, and didn't investigate possible compensation of the dimensional deviations through the use of different parameter sets. Characterizing the LS process of PA12 for different parameter sets by using several different test artefacts (as done in [5-6]), would require an extensive production and financial effort. In order to reduce the number of test parts needed for the process characterization, it would be necessary to combine the features included in the different test artefact into one artefact, reducing the build volume needed to perform the characterization of one parameter set. In principle, the design freedom given by the LS process would allow to place the required features into a complex design, keeping the required part's volume to a minimum. However, complex designs are difficult to measure using traditional Coordinate Measurement Machines (CMMs), since they need a line of sight to acquire a point cloud. A solution to this limitation is the use of X-ray Computed Tomography (CT), which is a non-destructive measuring method that allows to measure both internal structures as well as the porosity of the material [7]. The CT-projections are reconstructed into a 3D voxel model, which allows the user to assess a large amount of measuring points at the same time.

In this work we present a new design for a test artefact, which contains small holes and slots having different sizes and orientations. These features are placed in both horizontal and vertical walls, having a range of four different wall thicknesses, for a total of 376 different combinations. The aspect ratio of the artefact was kept close to one, in order to reduce the part's volume to a minimum. X-ray Computed Tomography is used to measure the dimension of each feature of the test artefact, allowing a complete overview of the influence of the different factors on the local dimensional deviations. The aspect ratio of the artefact allowed a more uniform X-ray penetration in all directions during the CT data acquisition, improving the quality of the reconstructed 3D voxel model. In a same LS-PA12 build, the artefact has been printed using several scanning strategies, allowing in this way to define the influence of the different process parameters on the dimensional deviations. Based on the obtained results, a discussion of the possible strategy to compensate for the dimensional deviations is provided.

2. Methods

2.1. Artefact Design

The test artefact used in this work took into account requirements regarding both the CT measurement and LS process. The features object of the study have been arranged into the design, in a way that allowed to keep the total part's volume to a minimum. A cylindrical shape was chosen, since it allows to keep the penetration length more or less equal in all the projections.

The features investigated in this study are holes and slots. The artefact contains several different sizes of these features placed both in vertical and horizontal walls. In order to assess the influence of the wall thickness on the resulting dimensional accuracy, four thickness levels have been chosen: 0.6, 1, 2.5 and 4 mm. Figure 1a and 1b show how the different features are arranged in the vertical (external cylindrical walls of the artefact) and horizontal (internal part of the artefact) walls. Figure 1c shows the set of holes with a diameter ranging from 0.6 to 1.3mm (steps of 0.1 mm), positioned in the vertical walls. Figure 1d set of horizontal and vertical slots with a width ranging from 0.6 to 1.2 mm (steps of 0.2 mm), positioned in the vertical walls. In order to assess the influence of the layer slicing, these sets of features (e.g. holes and slots) are positioned four times around the cylindrical artefact at every 90 degrees, where each set's position decreases by a height of 30 microns. The four sets of features cover four different positions within a height of 120 microns, which equals the layer thickness used during the process. Contrary to the features placed in the vertical walls, the ones placed in the horizontal planes are not affected by the layer slicing. On the other hand, preliminary experiments have shown they present a higher dimensional deviation compared to the vertical ones, especially the holes [6-7]. For this reason, the nominal diameters of the holes placed in the horizontal planes range from 0.6 to 2.1 mm (steps of 0.1 mm). Contrary to the holes in the vertical walls, these ones are placed only in one position. Table 1 resumes the dimensions of holes and slots placed in the horizontal and vertical walls.

Table 1 Dimensions of the holes and slots placed in the horizontal and vertical walls.

	Horizontal	**Vertical**
Holes (Diameter)	0.6-2.1 mm (steps of 0.1 mm)	0.6-1.3 mm (steps of 0.1 mm)
Slots (Width)	0.6-1.2 mm (steps of 0.2 mm)	0.6-1.2 mm (steps of 0.2 mm)

The test artefact contains in total 376 features to be measured. In order to facilitate the dimensional measurements, some aligning cylinders were included in the design (bottom left and bottom right of Figure 1a). Four of these cylinders are positioned at the bottom of the artefact, two oriented in the vertical direction and two in the horizontal one. The role of these aligning cylinders is to help, and improve, the 'best fit' alignment of the 3D voxel model on the CAD file. This is a necessary step to automate the workflow used to perform the dimensional measurements, which strongly decreases the time needed to process the data.

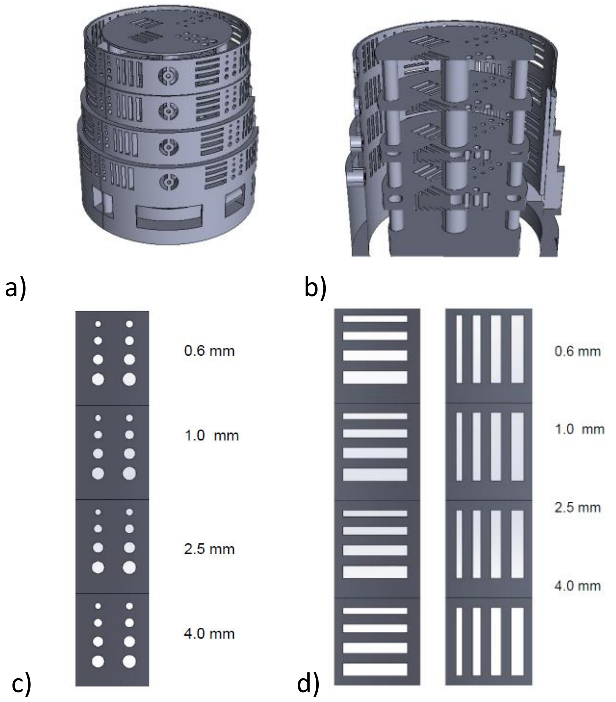

Figure 1: (a) CAD model of the test artefact used to determine the dimensional accuracy limits of laser sintered PA12-parts; (b) cut-view of (a); c) View of the holes place in the vertical walls; d) View of the slots place in the vertical walls.

2.2. Samples production

The test artefacts are produced in a state-of-the-art laser sintering machine, equipped with the new Materialise Control Platform (MCP) [10] using a PA2200 PA12 powder with a mixing ratio 50/50 between virgin and recycled powder, a layer thickness of 120 microns and an alternate x-y scanning pattern. In order to investigate possible ways to compensate for the dimensional deviations different scanning strategy have been tested, which differed only in beam compensation (e.g. offset between the real edge of the part and the position of the contour vector) and laser power of the contour vector. These two parameters have been selected, since they contribute the most to the position and amount of the energy delivered at the edge of the feature, namely they are supposedly the ones influencing the most the local dimensions. Three levels of each of the two process parameters have been selected, leading to nine different combinations and scanning strategies. Table 2 shows the common process parameters used during to manufacture the test artefact, while Table 3 resumes the different levels of beam compensation and laser power of the contour vectors. The reference beam compensation value (e.g. 0.2643mm) was determined using a dedicated artefact, manufactured with a contour laser power of 34W. Based on the values reported in Table 3, the scanning strategy that should yield the smallest dimensions is the combination of the minimum beam compensation (e.g. 0.2043mm) and the maximum laser power (e.g. 34W), while the one that should yield the largest dimensions is the combination of the maximum beam compensation (e.g. 0.2643mm) and the minimum laser power (e.g. 26W). For simplicity further in the text these scanning strategies will be referred as 'small' and 'large', while the reference scanning strategy (e.g. 0.2643mm, 34W) will be referred as 'normal'.

Table 2 Common process parameters for all the scanning strategies.

Contour Vectors scanning speed (mm/s)	Hatching Distance (mm)	Hatching Vectors scanning speed (mm/s)	Hatching Vectors Laser Power (W)
3000	0.3	4000	40

Table 3 Different values of beam compensation and laser power of the contour vectors used to manufacture the test artefacts.

Parameters	Levels
Beam compensation (mm)	0.2643; 0.2343; 0.2043;
Laser power contour vectors (W)	34; 30; 26

2.3. X-ray Computed Tomography

All CT scans have been performed using a 225 kV CT machine from Nikon Metrology using a Molybdenum target, a voltage of 110 kV, a current of 127 µA and 3000 projections [9-10]. The magnification used was x6 yielding a voxel size of 33 µm. The reconstruction of the projections into the voxel volume (in float 32 bit format) is performed using CT Pro 3D software from Nikon Metrology. The CT dataset is analysed using VGstudio max v. 3.0 (VGS) from Volume Graphics GmbH. Due to the high number of features included in the test artefact, the workflow to perform the dimensional measurement within VGS was automated. The first step is to register the 3D voxel model with the original CAD file used to produce the object. This registration is performed by using the option in VGS: 'best fit against multiple geometry elements', where the aligning cylinders described in section 2.2 are given as reference, helping and improving the registration accuracy. The second step is the definition of a 'Measurement Template' (MT) that defines a geometry element for each feature to be measured. The geometry elements are defined directly on the CAD file by using the 'CAD selection' option in VGS. This option allows to create automatically fit points on the surface of the patch of the CAD model by just clicking one time on the surface and by indicating the type of element to be fitted: plane, cylinder, sphere, etc. A fit point density with a step of 0.01 mm was used for all the geometrical elements. The holes are defined by fitting a maximum inscribed cylinder on the CAD file, while the slots are measured by fitting two parallel planes, one to the top and one to the bottom of the slot. The distance between the two planes is the width of the corresponding slot. The MT defined above is the same for all the test artefact to be measured. By applying the MT on the 3D voxel model, the geometrical elements defined are refitted (Gaussian best fit) on its surface, allowing to measure both dimensions and tolerance of the feature. The choice of a sufficiently high searching distance ensures that the point cloud defining each geometrical element in the CAD file can be refitted on the surface of the 3D voxel model. Due to the rough surface of the printed test artefact and the dimensional deviations, the geometrical elements were not always perfectly aligned with the original geometrical element from the CAD file. In order to avoid these misalignments, and consequently incorrect feature size measurement, the main axis of the cylinders and the normal of the planes were fixed while defining the geometrical elements to be fitted in the MT. Figure 2 and 3 show examples with and without the axis/normal of the cylinders/planes fixed. As a final step, a macro was registered and all the CT datasets batch processed in sequence, allowing in this way to automate the dimensional measurements.

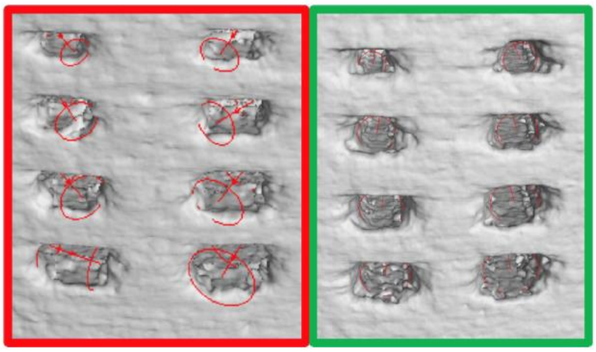

Figure 2: Cylinders geometry elements fitted on the holes in the vertical walls with (left) and without (right) having the axis of the cylinder fixed.

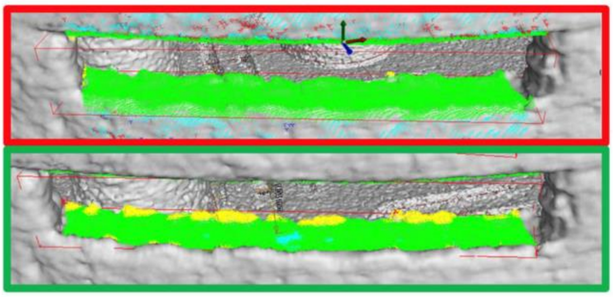

Figure 3: Planes geometry elements fitted on the slots in the vertical walls with (left) and without (right) having the normals of the planes fixed.

3. Results and Discussion

Due to the high number of dimensional measurements carried out, it is not possible to present all the results gathered during this study, but only a condensed part containing the main highlights. Figure 4 shows a comparison between the dimensional deviations from the nominal diameter values of the holes placed in vertical and horizontal walls of the test artefact produced with the normal parameter set. The holes placed in horizontal planes are much smaller than the ones in the vertical walls, with the smaller holes (e.g. 0.6-1.1 mm diameter) not shown because completely or partially closed. For vertical wall orientations the dimensions appear to decrease with increasing wall thickness. Figure 5 shows that this large difference is present also for the 'small' and 'large' scanning strategies, namely is present for all the parameters combinations tested.

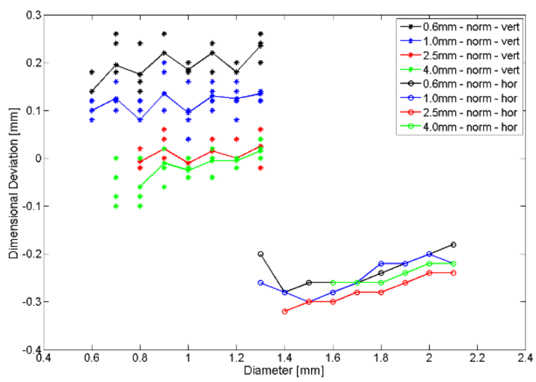

Figure 4: Comparison between the dimensional deviations of the holes positioned in vertical and horizontal planes of the artefact produced with the 'normal' parameter set. The markers connected with solid lines represent the mean values, while the other markers represent the individual measurements.

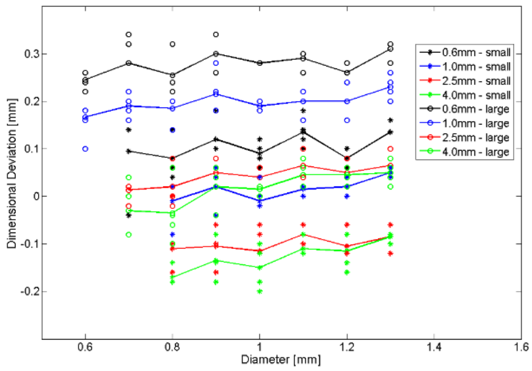

Figure 5: Comparison between the dimensional deviations of the holes placed in the vertical walls of artefacts produced using the parameter sets: 'small' and 'large'. The markers connected with solid lines represent the mean values, while the other markers represent the individual measurements.

The big spread between the individual measurements of the four positions of each hole visible in Figure 4 and Figure 5 are related to the different positioning heights, namely to the layer slicing effect. Figure 6 shows the cross section of point clouds (exported from VGS) of the same hole printed in the four positions. The shape and diameter of the holes is strongly affected by the number of slices which constitute the holes.

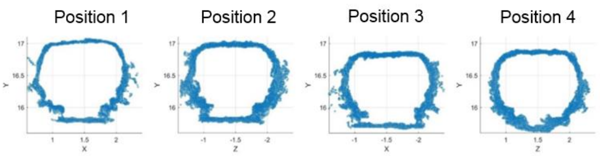

Figure 6: Cross section views of the point clouds (exported from VGS) relative to the holes with a diameter of 1.3mm positioned in the vertical wall with a thickness of 4.0mm produced using the 'normal' parameter set.

However, the number of slices affects the dimensions of the holes only along the (vertical) printing direction, while at the (horizontal) layer level the parameters affecting the dimensions most are the beam compensation and laser power. Taking this in consideration, a change in beam compensation would affect the dimensions of the holes in the vertical walls only along one axis (ortogonal to the printing direction), while it would affect both axis of the holes in the horizontal planes. Also a change of the contour laser power can be expected to influence in a similar way the dimensions of the holes. Based on these considerations, the minimum difference in dimensions between holes placed in vertical and horizontal walls should be achieved for the 'large' scanning strategy, namely the maximum beam compensation and minimum laser power. Moreover, the dimensional difference between the two orientations should decrease for an increase in the wall thickness, as shown in Figure 4. However, Figure 7 shows that even for these process conditions, it is not possible to obtain similar holes' dimensions in both walls orientations. These results suggest the difficulties in finding a single beam compensation value which allows to obtain similar dimensions for a same hole placed in walls which differ for thicknesses and orientations.

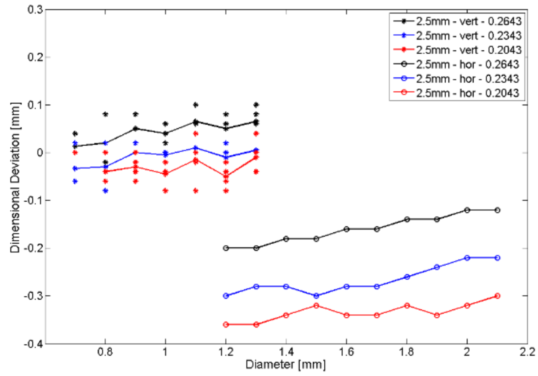

Figure 7: Comparison between the dimensional deviations of the holes positioned in vertical and horizontal planes with a wall thickness of 2.5mm, relative to the artefact produced with a contour laser power of 26W and different beam compensations. The markers connected with solid lines represent the mean values, while the other markers represent the individual measurements.

Figure 8 and Figure 9 show that while the horizontal slots placed in the vertical walls are affected in a limited way by the scanning strategy, the vertical ones result to be strongly affected by it. In the first case, the factor influencing the most the dimensions is the slicing while in the second one, both beam compensation and laser power play a major role. However, none of the slots placed in the vertical walls were closed. On the other hand, Figure 10 shows that many of the slots placed in horizontal walls were completely or partially closed. This behaviour is similar to the one of the holes placed in the same planes. As for the holes, these results suggest the difficulties in finding a beam compensation value which allows to obtain similar dimensions for a same slot placed in walls which differ in thickness and orientation.

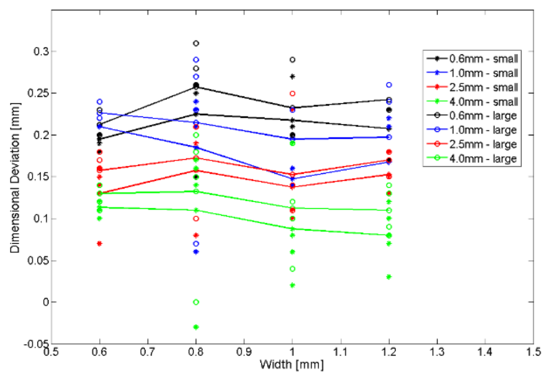

Figure 8: Comparison between the dimensional deviations of the horizontal slots placed in the vertical walls of artefacts produced using the parameter sets: 'small' and 'large'. The markers connected with solid lines represent the mean values, while the other markers the individual measurements.

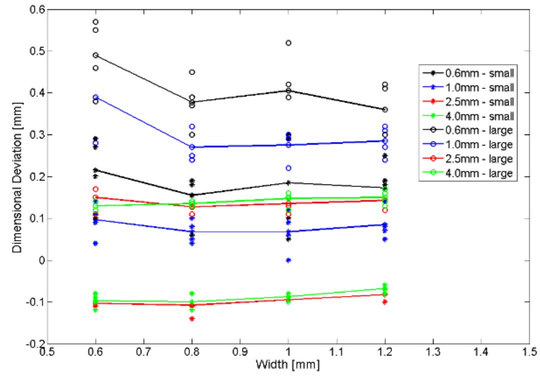

Figure 9: Comparison between the dimensional deviations of the vertical slots placed in the vertical walls of artefacts produced using the parameter sets: 'small' and 'large'. The markers connected with solid lines represent the mean values, while the other markers the individual measurements.

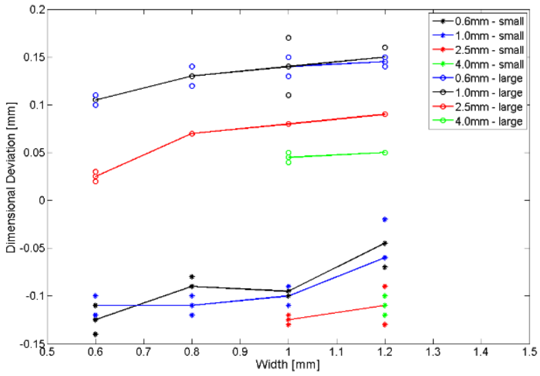

Figure 10: Comparison between the dimensional deviations of the slots placed in the horizontal walls of artefacts produced using the parameter sets: 'small' and 'large'. The markers connected with solid lines represent the mean values, while the other markers the individual measurements.

The investigation conducted shows how the local processing conditions strongly influence the dimensions of holes and slots, as well as the difficulties to define a unique beam compensation value that allows to obtain all the features' dimensions correct. Partial compensations are possible if the part to be manufatured contain the same features printed in similar processing conditions. In this case the scanning strategy can be tailored to minimize the dimensional deviations. Another possible way to compensate for this dimensional deviations is an 'a priori' approach, which consist in modifying the actual size and shape of the feature in the part, in order to obtain the right dimensions after printing. On this regard, the work carried out in this study provides initial information on how to modify the CAD file.

4. Conclusions

In this work a new test artefact design for dimensional characterization of the Laser Sintering process was proposed. The test artefact contains small holes and slots having different sizes and orientations. These features are placed in both horizontal and vertical walls, having a range of four different wall thicknesses, for a total of 376 different combinations. The aspect ratio of the artefact was kept close to one, in order to reduce the part's volume to a minimum, and allow a more uniform X-ray penetration in all directions during the CT data acquisition. The test artefact was printed using several scanning strategies, which differed in beam compensation (distance between the edge of the part and the first contour) and contour laser power. These two process parameters were selected because of their significative influence on the local features' dimensions. All the artefact have been characterize by means of X-Ray CT. The analysis of the CT datasets was performed with the VGStudio max software, where a dedicated measurement protocol for each feature type was developed. The dimensional characterization showed that both holes and slots are strongly affected by the thickness of the wall where they are positioned, where an increase in wall thickness determined a decrease in the dimensions of the feature. Even though the horizontal walls yielded smaller features' dimensions, the influence of the wall thickness appeared to be larger for holes and slots positioned in vertical walls. For both types of features, none of the scanning strategy demonstrated to be able to produce similar dimensions for a same feature placed in different positions. In fact, the local processing conditions influence in different ways the dimensions of holes and slots, leading to the impossibility to define a unique scanning strategy that allows to obtain correct dimensions for all the features. There are not ready solutions on the market that allow to completely compensate for such dimensional deviations. However, when the features have the same size and local processing conditions, it is possible to tailor the scanning strategy in order to minimize the dimensional deviations. Another way to compensate for this dimensional deviations would be to perform 'a priori' compensation. This approach would consist in modifying the actual size and shape of the feature in the part, in order to obtain the right dimensions after printing. The work carried out in this study provides initial information on how to modify the file before printing, but it cannot be considered exhaustive of all cases. This approach, would be particularly efficient when applied to mass customized parts, namely parts that are slightly different, but present the same collection of features.

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