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Geometrical and feature of size design effect on direct stereolithography micro additively manufactured components

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Abstract

Additive manufacturing (AM) is a suitable technique for the production of components with different geometries and complexity that cannot be easily fabricated with traditional manufacturing techniques. However, considering the manufacturing restrictions can clarify the feasibility of the designs to be produced by AM. In this context, this study investigates the capability and limitations, in terms of feature size and geometry, of the Vat Polymerization method by producing various micro components. In order to evaluate the AM machine capability, two test parts, one with hollow cylindrical and the other with hollow box shapes, with different size features have been designed. Different batches of samples were printed to find out the limit for micro polymer components manufacturing with different geometries. The variability of the results in a single print and different batch was also evaluated. The smallest printed feature of size with hollow shape was 630 µm for both geometries and the features smaller than 355 µm were completely solid.

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Keywords: Additive manufacturing; Vat polymerization; Micro manufacturing; Stereolithography; Polymer

1. Introduction

Additive Manufacturing (AM) is a technology capable of manufacturing a 3D model directly from a 3D CAD by adding material in layers. Therefore, AM is able to rapidly fabricate a wide variety of parts cost-effectively without the need for process planning, which allows easy product customization. For this reason, this technology was initially used to produce prototypes (Rapid Prototyping). Due to the recent improvements in AM technologies, parts produced by AM are already suitable for end use and, currently, AM has a wide range of applications (Stampfl et al., 2014). Nevertheless, the time required for the production of one part and its economic cost makes AM still inadequate for mass production, being other technologies like injection molding (IM) more advantageous.

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The fact that AM technologies create parts layer by layer allows them to fabricate complex 3D geometries that cannot be achieved by subtractive manufacturing methods, like machining technologies. Due to the broad range of materials that AM is able to process and the functional and geometrically complex structures that is able to achieve, AM is rapidly increasing its significance. The latest improvements in AM accuracy have allowed the production of micro size components, introducing AM into the micro manufacturing field (Vaezi et al., 2013). The increasing use of micro components in many industrial sectors has led to many advances in the area of micro manufacturing and the research of the applications of micro additive manufacturing (μAM) is gaining great importance (Lifton et al., 2014). In Vaezi et al. (2013), a review of 3D μAM techniques is presented. From them, Vat Photopolymerization (VP) methods like Stereolithography (SLA) and Digital Light Processing (DLP) were highlighted. They are considered scalable AM methods because they can be applied both in normal-size and micro-size manufacturing.

Design for AM methodologies is a key element for the economically successful introduction of AM in the industry. This implies that some parts need to be redesigned to make the most of AM benefits and overcome its challenges. For instance, Hällgren et al. (2016) and Salonitis et al. (2015) propose the use of a lattice or framework to (re)design and then produce a lightweight and functional component. The design has to take into account the material selection, the process selection, and the post processing, as well as time and cost implications (Vaneker, 2017). The performance and capability of the AM machine has a great influence on the final product; therefore, it is important to know them and consider them during the design phase. Different designs with the same setting can achieve different performance (Davoudinejad et al., 2018).

This current investigation analyzes performance of a SLA AM machine in terms of geometry and printing feature size when manufacturing micro-features with different geometries, while keeping the machine settings constant. This work is based on a previous study of Davoudinejad et al. (2017), where a DLP proprietary printing machine was characterized by printing a test part with micro features. In contrast to the study here presented, in Davoudinejad et al. (2017), only one type of geometry was printed considering different values for the following machine settings: layer thickness, exposure time and light intensity.

Here, the AM method used for the experiment is defined, and then the test parts designed for the study are described. Then, after the measurement procedure is briefly introduced, the results are presented and conclusions are deduced.

2. Additive Manufacturing Method and Post Processing

The AM technology subject of this study is a Vat Photopolymerization method. In a VP process, an ultraviolet (UV) light cures, i.e. hardens, the liquid photopolymer resin laid in a vat, and the features are produced by slices one on top of another by tracing 2D contours of a CAD model using UV light. In this specific case, the technology used is Stereolithography (SLA), in which the UV light is radiated by a laser beam, solidifying the resin in the vat in a point-by-point style (Mems, 2008). Fig. 1 shows the schematic of a typical SLA machine.

This study analyzes the performance of the SLA machine in terms of geometry and size, when printing two different kinds of micro-geometry in different sizes, in order to maximize the product performance for the feature shape and size.

In order to inspect the performance of the printout, five different batches were printed in different days. The printing time for each batch was about hundred minutes. Table 1 shows the selected parameters combination used for 3D printing. When printing with SLA method, support structures are necessary to create the parts since the viscosity of the photopolymer alone is not enough to support free hanging geometries. For the printed features, the base was considered on the bottom of the design and, in addition, the printing software added the support at the bottom of the base design for each part.

After the machine has finished printing the part, it is necessary to remove it from the vat and clean the liquid resin that remains on the sample. This is done with isopropyl alcohol (IPA). Once the part is clean, it is dried with pressurized air. Afterwards, to complete the curing of the photopolymer, the part is placed in a UV oven for 80 minutes.

Table 1. Experimental conditions.

Parameters	Selected Parameters
Layer thickness /μm	25
Photopolymer resin	Clear FLGPCL02
Printing resign temperature /°C	31

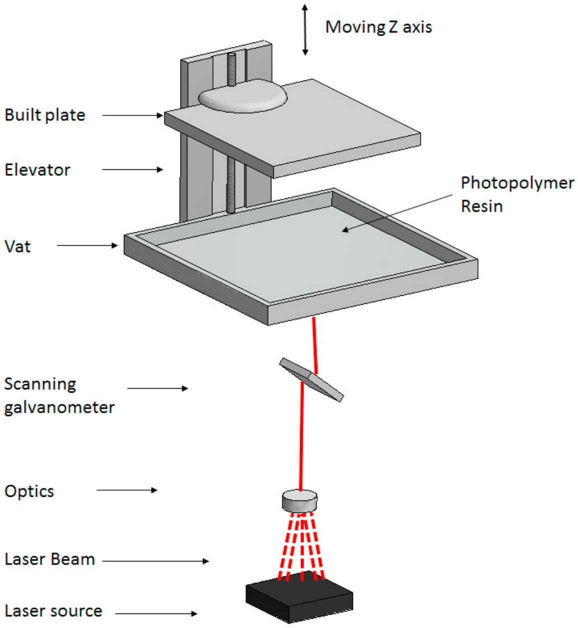


Fig. 1. Schematic of the SLA technology 3D printing process

3. Sample Parts design

Although AM technologies are able to create very complicated parts, the design of the parts is critical due to the manufacturing restrictions of the process. In order to find out the limit of 3D printing, in terms of the smallest additively manufactured features and the geometry of the parts, various designs were used to cover different geometries in the micro scale. Two different shapes were considered: hollow box and hollow cylinder. One test part was designed for each shape. In each part, the features are positioned in a matrix of 6×20, as shown in Fig. 2, with a specific distance of 250 µm between each other and a 3:4 aspect ratio for the lateral size. In each column of the matrix the size of the features decreases from top (1.5 mm in diameter/width) to bottom (6 µm in diameter/width). The six columns of each part are equivalent. The base of the part is 12×12×2 mm^3. The features raise the maximum height of the test part to 500 µm. The geometries were designed to observe the accuracy of micro printed features in different shapes.

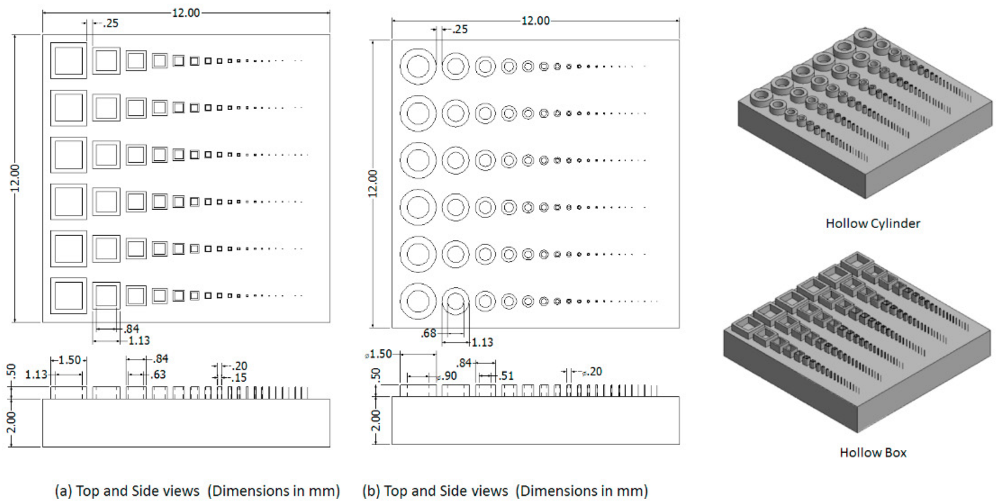


Fig. 2. Top and side views of (a) hollow box, (b) hollow cylinder and isometric views

4. Measurement procedure

The measuring of the test part features was performed using an Alicona Infinite Focus 3D microscope. Due to the semi-transparent material, the sample measurements were challenging to process. Therefore, based on the sample geometries, different measurement settings were applied for acquisition of the features. Measurement parameters were as follow: 10× magnification, exposure time = 217-630 ms, contrast = 0.59-0.67, estimated vertical and lateral resolutions, 200 nm and 3 µm, respectively. A post-processing software was employed for extracting the measurement results (SPIP). Moreover, a scanning electron microscope (SEM) was used for qualitative observation. Due to the non-conductivity of the material, a fine stream of carbon was deposited onto the samples prior the acquisition of the SEM micrographs.

5. Results

The printed part samples for both designs are presented at Fig. 3. Printing results were evaluated, in terms of geometry and printable feature size of the samples, by comparison to the CAD model. Fig. 4 shows the SEM pictures of the features printed in different dimensions. The 15 features were fabricated in each row with a smallest diameter dimension of 26 µm for both the hollow box external side and the hollow cylinder external diameter.

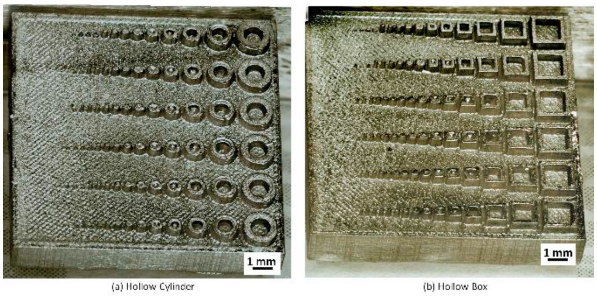


Fig. 3. The printed features: (a) cylinder; (b) box

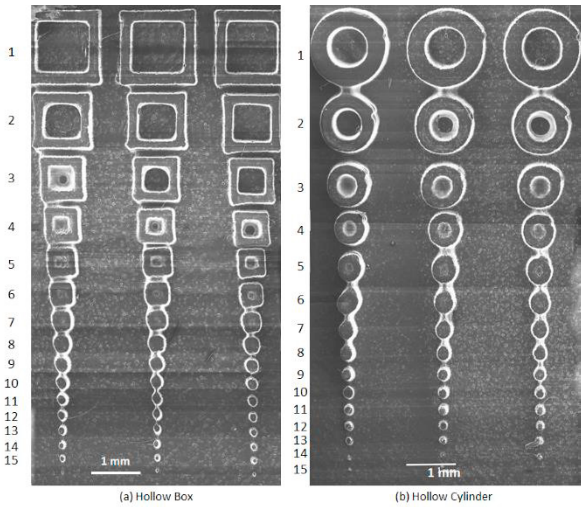
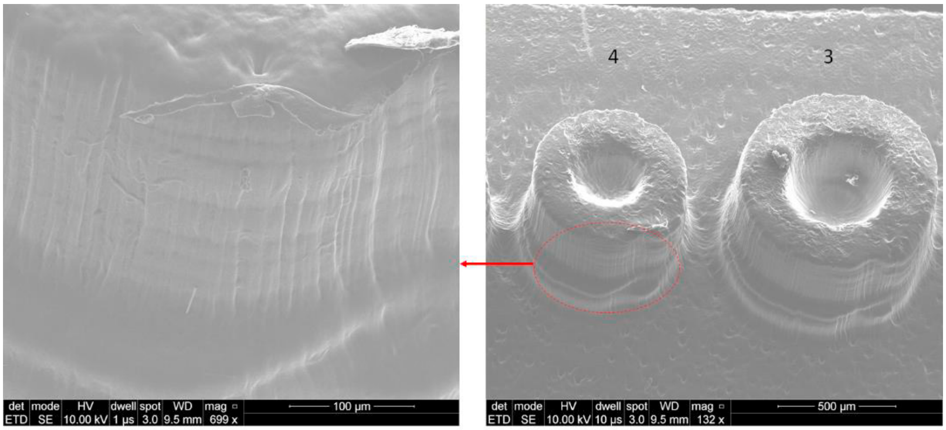


Fig. 4. SEM pictures of the samples in top view: (a) box; (b) cylinder

In both cases, the smallest hollow features were printed in the fourth row, with a dimension of 630 µm, after this row, the holes were unintendedly filled with resin. The post processing might also affect the hollow shapes of the features if the left over resins are not cleaned properly. However, the total quantity of hollow pillars was slightly smaller for the cylindrical shape. Fig. 4(a) shows that the smallest hollow box printed having a square base is in row 6, with a dimension of 355 µm- After row 6, the shape of the printed pillars is distorted and changes to cylinders. In the CAD model, there were 20 rows, and the smallest feature had a dimension of 6 µm. Nevertheless, as it can be seen in Fig. 4(a) and (b), in both cases, the smallest feature printed is in row 15, with a dimension of 26 µm and it has the shape of a solid cylinder. Therefore, the SLA machine was not able to print the consecutive pillars, this shows the voxels limit of the 3D printer used for features fabrication with SLA method. Fig. 5(a) shows the magnification of printed wall with visible printed layers and Fig. 5(b) illustrates higher magnification of the 3rd and 4th rows from the cylindrical shape. It is visible the 4th row was the last component which was hollow partially and the most of the resin was left inside the hole.



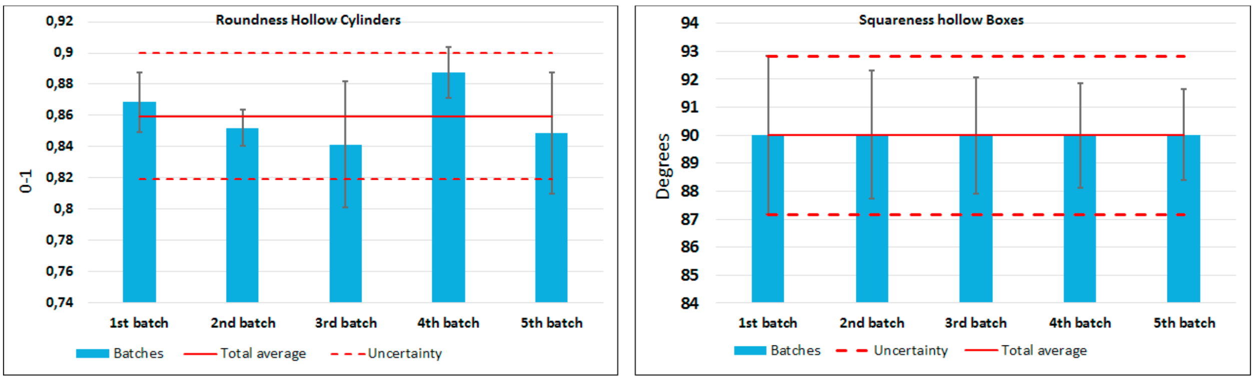
(a) (b)

Fig. 5. Hollow cylinder (a) printed wall magnification (b) third and fourth rows

In order to find out how close to the CAD model the geometries of the two designs were fabricated, the features were evaluated in terms of circularity for the hollow cylinders and squareness for the hollow boxes, always in the outer surfaces. The circularity for the external surface of the hollow cylinder was evaluated according to ISO 9276-6. The shape of the circularity was measured as a ratio that represents the degree to which the particle is similar to a perfect circle, considering its form and roughness (Equation 1). It has a value from 0 to 1, being 1 a perfect circle.

$$C = \sqrt{\frac{4\pi A}{P^2}} \quad (1)$$

The result values were calculated using SPIP tool for feature analysis. The average circularity varies for each batch, as it can be seen in Fig. 6(a), where, in addition, the standard deviation of the circularity inside each batch has been represented in the error bars. The average circularity taking into account all the batches is 0.86, having a standard deviation of ±0.05, considering a uniform distribution. The squareness of the hollow boxes was calculated by measuring the angles of the square edges. In a parallelogram, the sum of the measure of all the angles is 360° therefore, the average is always 90°. Nevertheless, the four angles of the boxes were measured separately and the average value was calculated, being 90, 01°. For this reason, in this work, the squareness is evaluated by the deviation of every angle from the right angle. In Fig. 6(b), the standard deviation of the resulting deviations has been represented in the error bars and, as it can be observed, it is slightly different for every batch, but of the same order of magnitude. When all the batches are taken into account, the standard deviation is ±2.9°, considering always a uniform distribution.



(a) (b)

Fig. 6. (a) Circularity results for hollow cylinders; (b) Squareness for hollow boxes

6. Conclusion and future work

This study analyzed the geometry and size of micro-features printed by an AM machine using SLA technology. Two different test parts have been designed, each one having different kind of features: hollow cylinders and hollow boxes. In each sample, the same features are present in various sizes, going from a maximum width/diameter of 1.5 mm to a minimum of 6 µm. In each test part there are 6 features of each size, and the test parts were printed in 5 batches in different days. The smallest possible size printed for both the hollow box and the hollow cylinder were analyzed for each sample. The boxes presented slightly more printed hollow features. However, in both geometries the features smaller than 630 µm were not hollow. For the features with sizes between 470 and 355 µm, it was observed that, even though they were not completely hollow, the hollow pattern was somehow present on the top of the features. The features smaller than 355 µm were completely solid. This can be due to the limit of SLA machine for printing the thickness of the feature walls. For the same reason, in the test part with hollow boxes, the shape of the features with a size of 355 µm or smaller changed to cylindrical. In both cases, hollow boxes and cylinders, the smallest feature printed, regardless of its shape, was 26 µm, which shows the voxel limit of the printer. The geometries were analyzed by the circularity for the hollow cylinders and the squareness for the hollow boxes. The sharp edges of the boxes were not printed accurately. Moreover, the angles of the edges presented a standard deviation of ±2.9°. Regarding the hollow cylinders, an average circularity of 0.86 was observed, having a standard deviation of ±0.05.

In future works, the influence of the feature of size on the circularity will be also addressed and different types of geometries will be added to the study to evaluate various geometrical features. Future works will also include an analysis of the machine precision in dimensions along the three axes when printing features with different geometries.

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